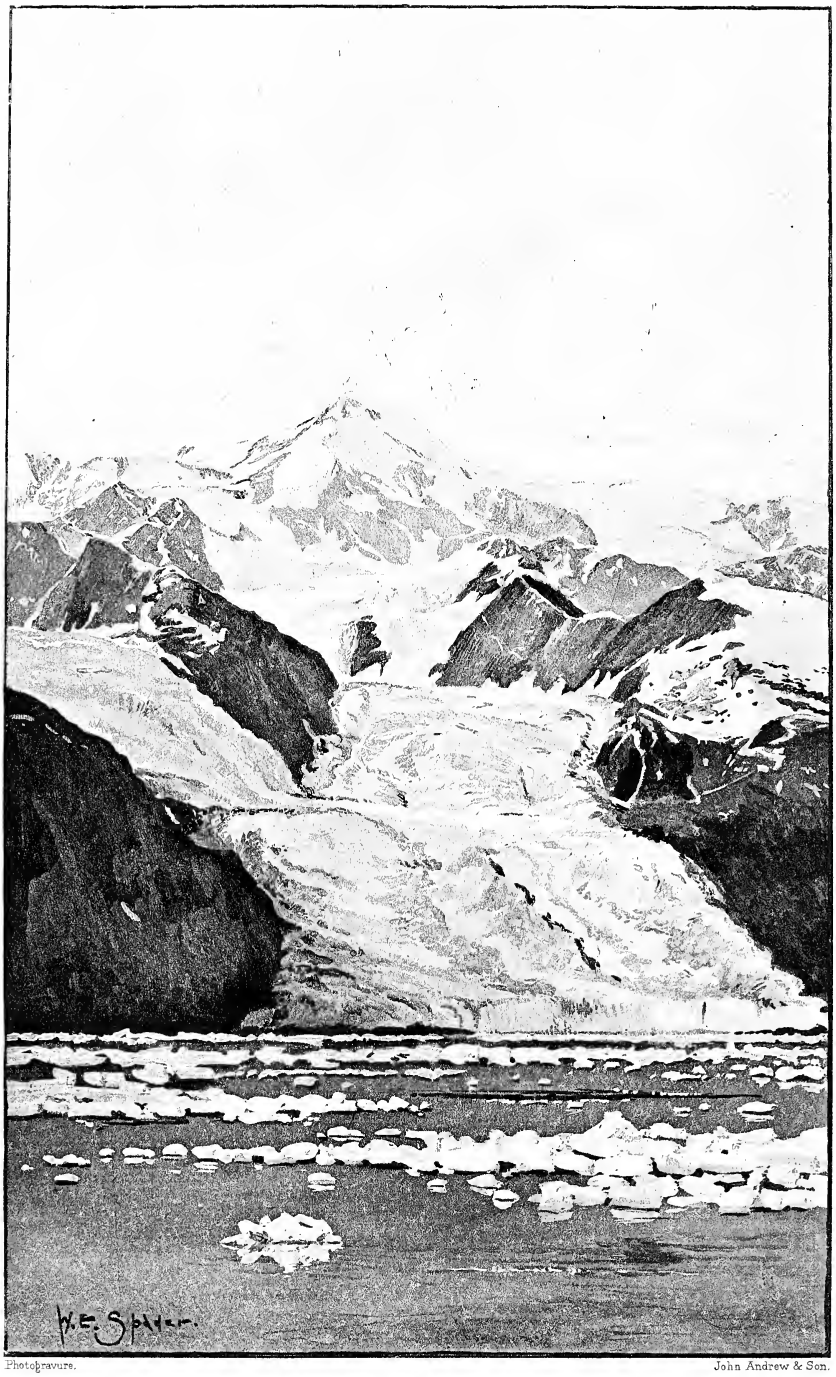
ALASKA

VOLUME III



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BRYN MAWR GLACIER

SMITHSONIAN INSTITUTION

HARRIMAN ALASKA SERIES

VOLUME III

GLACIERS AND GLACIATION

BY

GROVE KARL GILBERT

(Publication 1992)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
1910

ADVERTISEMENT.

The publication of the series of volumes on the Harriman Alaska Expedition of 1899, heretofore privately printed, has been transferred to the Smithsonian Institution by Mrs. Edward H. Harriman, and the work will hereafter be known as the Harriman Alaska Series of the Smithsonian Institution.

The remainder of the edition of Volumes I to V, and VIII to XIII, as also Volumes VI and VII in preparation, together with any additional volumes that may hereafter appear, will bear special Smithsonian title pages.

Smithsonian Institution,
Washington, D. C., July, 1910

HARRIMAN ALASKA EXPEDITION
WITH COOPERATION OF WASHINGTON ACADEMY OF SCIENCES

ALASKA

VOLUME III

GLACIERS AND GLACIATION

BY GROVE KARL GILBERT

NEW YORK
DOUBLEDAY, PAGE & COMPANY
1904

PREFACE

The present account of Alaska Glaciers, by G. K. Gilbert, forms the third of the Harriman Alaska Expedition volumes and the first of the technical series. It is based on observations made by the author in the summer of 1899, while a member of the Expedition, supplemented by information and photographs from various sources, and is illustrated by 106 text figures and 18 plates. The volumes on Geology, Cryptogamic Botany, Insects and Crustaceans are to appear simultaneously with it. The volumes on Nemerteans, Oligochetes, and several other groups of Invertebrates, are ready for the press, and will follow as soon as they can be printed. The two volumes on Phanerogams, or flowering plants, are expected to appear early in the year 1904.

Acknowledgments are due the Canadian International Boundary Commission, the United States Biological Survey, and, especially, the United States Geological Survey, for the use of photographs and other illustrative material. The editor wishes also to express his appreciation of the drawings prepared for this volume by Mr. W. E. Spader and Mrs. Louise M. Keeler. The frontispiece, plate xi, and a large number of the text figures are by Mr. Spader, while all of the chapter headings are by Mrs. Keeler.

C. Hart Merriam,
Editor.

Washington, D. C.,
May 1, 1903.

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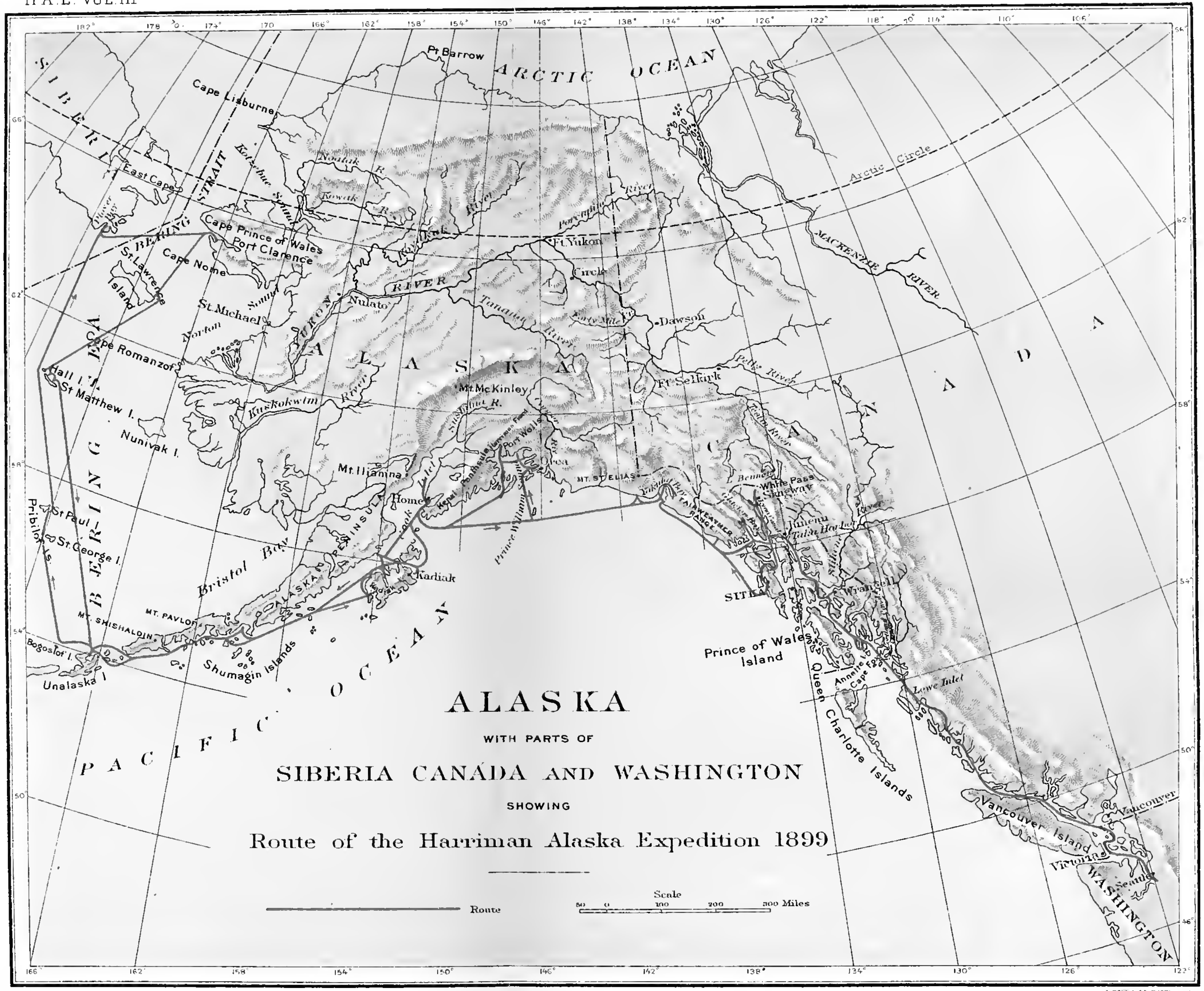

A. Hoen & Co. Baltimore

EXPLANATION OF PLATE II

MAP OF ALASKA, WITH PARTS OF SIBERIA, CANADA AND WASHINGTON

The map was compiled by Gilbert Thompson, under the direction of Henry Gannett, from published maps of the United States Coast Survey and from published and manuscript maps of the United States Geological Survey. The route of the Expedition is by Henry Gannett.

GLACIERS AND GLACIATION

BY GROVE KARL GILBERT

INTRODUCTION

THE glaciers of Alaska are many and the district through which they are distributed is large. The region formerly overrun by them is still larger. Ten years ago Russell and Kerr surveyed and studied Malaspina Glacier and its dependencies, and about the same time Reid made a scientific survey of Glacier Bay and its bordering glaciers; but these two tracts are only dots on the general map. All other glacial studies in the great field have been of the nature of reconnaissance and most of them have been carried on incidentally in connection with general geographic or geologic work. The Harriman Expedition added one more to the list of reconnaissances.

Until recently observations have been limited to the coast and it is still true that the greater number of glaciers which have been studied or mapped are coastal, or at least visible from the sea; but at the present time interior glaciers are receiving more attention, and knowledge of them is rapidly growing. Geographic investigation, so long as

stimulated by only the fur and salmon industries, was directed chiefly to coastal regions, but the development of gold placers turned attention to the interior, and for several years the topographers and geologists of the United States Geological Survey have been actively engaged in the exploration and survey of inland districts.

The growth of knowledge of Alaska glaciers is so rapid that a summary of existing knowledge would have but transient value. Generalization as to most points of world-wide interest is at present impracticable because observers have differed widely in their preconceptions and criteria, and the data consequently are not homogeneous. It has seemed best, therefore, to make the present report primarily a record of the data gathered by the Harriman Expedition and to make use of other material only when it is closely connected with the new data or is otherwise serviceable in their interpretation.

Regarded as a reconnaissance of glacial geology, the cruise of the 'Elder' was fairly comprehensive. It not only covered rapidly a wide extent of coast but it brought under view a great variety of phenomena. The general impressions acquired while the ship was skirting the coast were supplemented by the results of more definite and detailed observation at a few points on the land; and the impressions acquired by local studies of individual glaciers were enlarged by the panoramic view of many others. Opportunities for close examination included landings from the ship at thirty-four localities, at three of which the use of a camping outfit extended the time to several days. The remainder of the two months covered by the voyage was spent on the ship, and about half the sailing time was so conditioned by distance from shore, by light, and by weather, as to permit profitable observation of the coast. After the voyage was over physiographic studies were continued by the aid of photographs. Thousands of

views by members of the Expedition were examined, as well as a large number from other sources, and at least several hundred of these have yielded information as to glaciers and glaciation.

In arranging the material for presentation it has been found convenient to make an arbitrary division of the history of glaciation, connecting such changes as appear to have occurred within a few hundred years with the existing status, and classing all remoter changes with the geologic or Pleistocene series. This procedure is a matter of convenience only; it is not determined by a turning point in glacial history, but by a difference in the nature of the evidence by which the history is recorded. The direct observational record, for a few localities, reaches back a little more than a century, and inference from the age of trees extends a little farther; but for all earlier times the data are purely geologic and the changes have not been measured in years.

Under this classification the heads of my principal chapters are *Existing Glaciers* and *Pleistocene Glaciation.* The changing relations of sea and land also receive attention, but these are so closely connected with the problems of Pleistocene glaciation that they have not been given a separate place. Notes of a general character as to glaciers and their work are in part introduced along with local descriptions and in part assembled in a closing chapter.

Route. — Through the greater part of the journey I remained with the main party, so that the red line on the route map (pl. 1) shows my course with approximate accuracy. It seems necessary to mention here only a few deviations and details. Such dates as are of importance are noted in connection with the descriptions of individual glaciers.

In Glacier Bay I spent a day and a half at Muir Glacier, and then, with Muir and Palache, visited Hugh Miller,

Reid and Geikie inlets in a rowboat. This excursion occupied four days, three camps being made on the shores of the bay.

In Yakutat Bay I landed at Hidden and Nunatak glaciers and at the summer village of the Yakutat Indians. Two days were spent, with Muir, Gannett, and Kearney, in a boat excursion which visited Hubbard Glacier and Osier and Haenke islands.

In Prince William Sound I touched at Orca, and was then left at Columbia Glacier with a boat and shore party, including Palache, Coville, and Curtis, while the ship explored Port Wells. We remained three days, and afterward had a partial view of Harriman Fiord.

In Cook Inlet I was landed for a half day at Grewingk Glacier, while the ship made an excursion up the main bay.

I was with the ship on all routes about Kadiak Island, landed briefly on the western coast, spent several days at and near Kadiak village, and visited Long Island.

At Port Clarence I was of a party that crossed the bay in a launch and visited the mainland.

Photographs. — For the study of changes in the size of glaciers photographic views are of peculiar value. A view showing a glacier or part of a glacier in relation to details of adjacent land constitutes a record which can at any time be compared either with the objects themselves or with another photograph made in another year or month. That a photograph may have its highest value for such use its date must be known, including year, month, and day of month. The Harriman Expedition carried many cameras and secured a large number of views of glaciers. Some of these views are reproduced in the present and preceding volumes, and are thus made available for the investigator. So far as they are contained in this volume, their dates are given in the associated text.

The geographer who shall undertake in the future to study the variation of Alaska glaciers will have use not only for the fuller details of the original photographs but for a more complete series, and the following information is given for his benefit.

Of the many series of photographs made by the members of the Expedition, three may be regarded as public, and these also contain the most important records of the glaciers. Mr. E. S. Curtis, the official photographer of the Expedition, made the largest and best views, and keeps them on sale at his photographic establishment in Seattle, Washington. The negatives made by Dr. C. Hart Merriam are filed at the office of the Biological Survey, U. S. Department of Agriculture, Washington, D. C. My own negatives are filed at the office of the U. S. Geological Survey, Washington, D. C., where a set of prints may be seen and prints from negatives may be ordered.

The dates of our photographs for the several glaciers are as follows, the year 1899 being understood in each case: Amherst, June 26; Barry, June 26–29; Bryn Mawr, June 26; Cataract, June 27; Charpentier, June 11; Columbia, June 25–28; Crescent, June 26; Crillon, July 24; Davidson, June 6; Grand Pacific, June 12; Grewingk, July 21; Harriman, June 27; Harvard, June 26; Hidden, June 20; Hubbard, June 19–22; Hugh Miller, June 11; Johns Hopkins, June 12; La Perouse (near views), June 18; La Perouse (distant views), June 18 and July 24; Muir, June 8–13; Nunatak, June 20; Radcliffe, June 26; Reid, June 12; Roaring, June 27; Serpentine, June 26–27; Smith, June 26; Surprise, June 27; Turner, June 19–22; Vassar, June 26; Wellesley, June 26; Yale, June 26.

The table on page 6, giving series and negative numbers of photographs from which text figures were made, includes most of the figures based on photographic views. Information as to others is given in their labels and other

associated text. Titles of series are abbreviated in the table as follows: ESC = E. S. Curtis, Seattle, Wash.; USGS = U. S. Geological Survey, Gilbert; USBS = U. S. Biological Survey, Merriam, 1899; CBC = Canadian Boundary Commission, Ottawa, Canada. The Boundary Commission photographs are mounted in an album of many volumes, and the complete reference includes number, volume and page. A copy of this album is in the library of the State Department at Washington.

SOURCES OF PHOTOGRAPHIC MATERIAL USED IN TEXT FIGURES.

Figure.	Series.	Negative or Photo.	Figure.	Series.	Negative or Photo.
2	CBC	3, v. 12, p. 8	54	USGS	456
3	CBC	117, v. 12, p. 43	61	CBC	93-4, v. 14, p. 53
4	USGS	247	62	CBC	96, v. 11, p. 30
8	USGS	282	63	CBC	132-3, v. 8A, p. 50
9	USGS	270	64	USGS	222
12	CBC	44, v. 14, p. 13	65	USGS	324
13	CBC	38, v. 14, p. 11	66	USGS	470-471
14	USGS	259-261	67	USBS	293
15	USGS	257-258	68	USBS	55
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31	USGS	305	81	USGS	373
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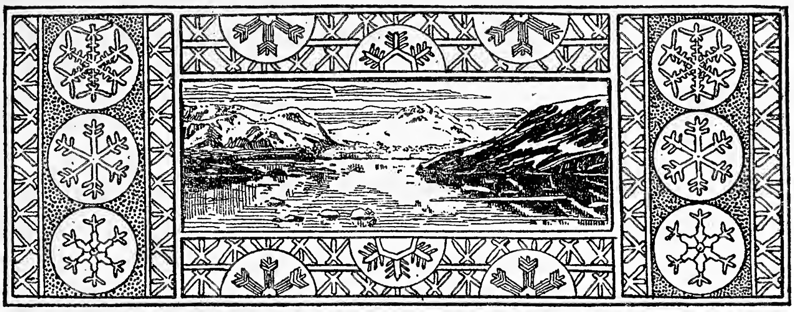
34	ESC	259	85	USGS	390
35	USGS	298-299	86	USGS	398, 400
38	USGS	355	87	USGS	392
39	USGS	356	88	USGS	402
40	USGS	352	90	ESC	393 (?)
41	ESC	311	91	USGS	433
43	ESC	275	92	USGS	430
45	USBS	117	93	USGS	443
46	USBS	137	96	USGS	346
49	ESC	280	97	ESC	304
50	USBS	151	102	CBC	3, v. 17, p. 3.
53	USGS	454-455			



CHAPTER I

EXISTING GLACIERS

GENERAL DISTRIBUTION

Nearly all the glaciers of Alaska are comprised within a belt of moderate width which follows the southern coast from the Aleutian Islands to Portland Canal (see fig. 1). Curving about the great bight of the Pacific Ocean known as the Gulf of Alaska, this belt has a length of 1,600 miles, and its extreme width, near the middle, is about 250 miles. Within it the arrangement of glaciers is irregular, but their more important groups occupy the middle region, while near the ends they are comparatively sparse and small.

The explanation of this massing of glaciers along the southern coast is not far to seek. The general circulation of the Pacific Ocean brings to the Gulf of Alaska a current of water which has been warmed in the tropics and still retains so much heat that its mean temperature is considerably above the normal for the latitude. The ocean is therefore, at most seasons, warmer than the contiguous land, and though air currents passing from ocean to land convey heat to the land they are themselves cooled.

While traversing the ocean the air becomes loaded with moisture, the cooling over the land diminishes its water-carrying capacity, and part of its load falls to the ground as rain or snow. Moreover, all this coast is mountainous, so that landward flowing air is compelled to rise, and its capacity is still further reduced by rarefaction. At the greater altitudes the ratio of snow to rain is comparatively large,

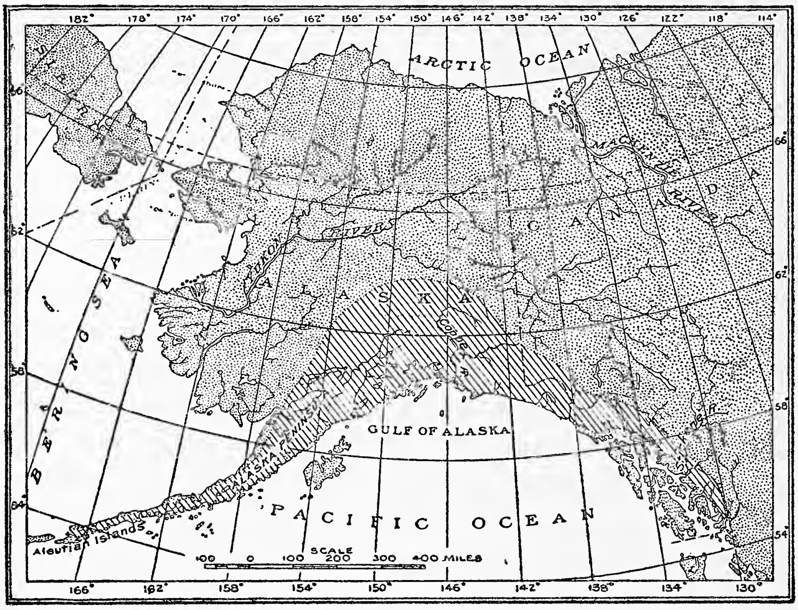


FIG. I. DISTRIBUTION OF GLACIERS IN ALASKA.
The belt containing glaciers is shaded by parallel lines.

and the mountains thus become gathering grounds for the snows that feed glaciers. Farther inland the air currents descend somewhat and the precipitation is diminished until the conditions for glacier formation cease. Hayes states that while the névé line of glaciers on the southward face of the St. Elias Alps lies at about 2,000 feet above sea-level, its altitude on the northern face is over 6,000 feet.[1]

[1] An Expedition through the Yukon district. By Charles Willard Hayes. Nat. Geog. Mag., vol. IV, p. 153, 1892.

Along the western coast of Alaska the conditions are different. Bering Sea lies practically outside the influence of the Pacific circulation and the temperature of its water is approximately normal. Its power to charge air currents with moisture is small, especially in winter; and though the winter temperature over the adjacent land is low, the snowfall is not heavy. There are no great mountain ranges to concentrate the precipitation, and the snow of winter, being broadly spread over plains or caught by ranges of moderate height, is dissipated by the melting and evaporation of summer.

The glacier-bearing belt includes about three-tenths of the vast territory of Alaska. Its exploration has but begun, yet enough is known to give it rank as the third great glacier district of the world, only the Antarctic continent and Greenland surpassing it. Its ice may be roughly estimated to occupy a tenth of the surface, or an absolute area of between 15,000 and 20,000 square miles, and this expanse is so divided and scattered as to offer to the student the utmost variety of local condition and detail. Of alpine glaciers, such as would receive individual names if near the homes of men, there are many hundreds, possibly more than a thousand; of broad, composite fields, like the Muir and Malaspina, there are about a half dozen; and more than thirty are known to reach the coast and cast bergs into the sea.

Skirting the land in a ship and making only brief excursions away from it, we saw only glaciers of the coastal mountains and lowlands, and close inspection was limited to the lower ends of ice streams. The phenomena which arrested our attention were those of wasting, of the deposition of detritus, and of the advance and retreat of the ice fronts. It soon became evident that our chief opportunity to advance glacial science was through contributions to the history of local changes in the frontal boundaries of

glaciers. That which was accessible to us had been accessible to our predecessors also, so that at several points we could compare present with past condition; and, for like reason, whatever record we might make could readily be used by the investigators of the future. Effort was accordingly made to visit as many as possible of the glaciers already described and mapped, and at all points visited to secure an intelligible record of the existing status.

The plural pronoun in the preceding paragraph is not the conventional affectation of modesty, but springs naturally from the consciousness that the facts I am to present were not wholly of my own observation. In grouping the material for publication it seemed to my colleagues in geology, Emerson and Palache, as well as to myself, that it would be better to classify by subjects than by observers, and as glaciers fell to my share, I have absorbed the glacial observations made by these gentlemen. I am greatly indebted also to the map work of Gannett, to the historical data and fertile suggestions of Muir, and to the timely cooperation of Dall and Coville.

Before taking up the description of the glaciers, a few words will be devoted to the terminology connected with their broader classification. The distinction between *alpine* glaciers (sometimes called glaciers proper) and *continental* glaciers (also called ice-sheets) has long been recognized. Alpine glaciers are fed by névés in high mountains and as rivers of ice descend mountain valleys. Continental glaciers gather on broad plains or plateaus and spread outward. Russell, as a result of studies in Alaska, recognized a third type, the *piedmont*.[1] A piedmont glacier is a broad sheet of ice resting on a lowland

[1] An Expedition to Mount St. Elias, Alaska. By Israel C. Russell. Nat. Geog. Mag., vol. III, p. 121, 1891.

at the foot of a mountain range, resembling a continental glacier in its mode of wasting, but distinguished by the fact that it is fed by the alpine glaciers of the mountain. An alpine glacier may be simple and separate, or compound. Two or more often descend from the same névé. Still more frequently two meet and coalesce after the manner of rivers, and a trunk glacier may have many tributaries. Small alpine glaciers are sometimes called *glacierets*, or, if visible high on the sides of mountain valleys, *hanging* glaciers.

For the purpose of the present report it is convenient to distinguish glaciers which reach the sea and discharge bergs, from those which end on the land. Reid calls these, severally, *tide-water* and *alpine* glaciers;[1] and they have also been called (after whose initiative I do not know) *live* and *dead* glaciers. Reid's use of 'alpine' conflicts with the well-established use already mentioned, and the terms 'live' and 'dead' are clearly misleading, as the great majority of the active glaciers of the world fail to reach the sea. I shall abbreviate 'tide-water' to *tidal* and employ *non-tidal* as its antithesis.

LYNN CANAL

The order in which the glaciers were observed was from east to west, and it has been found convenient to adopt this as the order of description also.

On the islands of southeastern Alaska there are no glaciers, and those of the mainland, south of Juneau, nestle in recesses of the mountains so far from the steamer route that we had only distant glimpses. But in Lynn Canal we followed a great fiord between ranges at once so lofty as to project well above the snow-line and so bold as to ex-

[1] Glacier Bay and its Glaciers. By Harry Fielding Reid. Sixteenth Ann. Rept. U. S. Geol. Survey, part I, 1896. See pp. 429 and 442. The term tide-water was used by Russell as early as 1892. See Am. Geol., vol. IX, p. 322, 1892.

hibit their crowning banks of snow and ice in continuous panorama. These ranges have been mapped in some detail by the U. S. Coast Survey and the Canadian International Boundary Commission, and it appears from a comparison of the glaciers with contours of altitude that the snow-line descends in both directions away from the fiord. On the mountain slopes overlooking the water glaciers do not form at a lower height than 4,500 feet, but

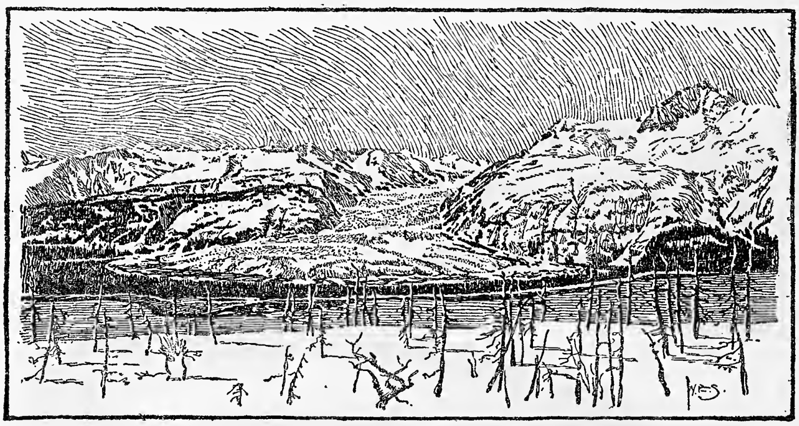


FIG. 2. DAVIDSON GLACIER, FRONT VIEW, 1894.

Showing the trench form of its valley, the spreading of its end, and the two zones of the fringing plain. Photograph by W. Ogilvie, from peninsula at left in fig. 3. See page 6.

on the opposite slopes of the same ranges 3,500 feet seems to be enough.

Davidson Glacier, fed by a high snow-field lying several miles back of the first mountain crest on the west, flows to the fiord through a narrow trench and reaches sea-level, though its ice does not actually touch the water of the ocean. In its mountain trench it has a width of only a half mile, but on escaping from the confining rock walls and entering the fiord it immediately spreads into a semicircular fan with a radius (in 1894) of about three-fourths of a mile. All about its frontal margin is a fringe of lowland averaging three-fourths of a mile in breadth, constituted, at the surface, of rock waste brought by the glacier.

There may be much unmelted ice beneath the visible gravel, but the lowland certainly contains a great body of gravel which, if glacier and ocean were withdrawn, would appear as a great curved ridge of water-laid moraine stuff. Glacier and moraine together encroach nearly two miles on the water of the fiord — a branch of Lynn Canal called Chilkat Inlet — reducing its width to about one mile.

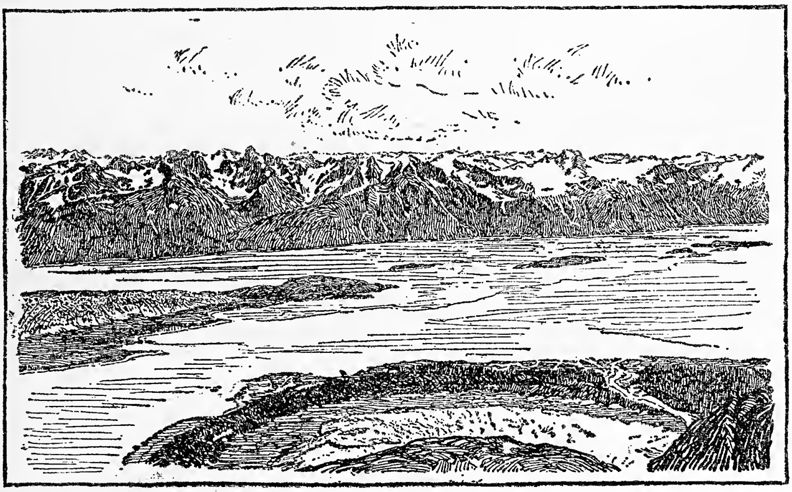


FIG. 3. DAVIDSON GLACIER.

View of terminal fan from the high peak at the right in fig. 2. Shows the barren and forested zones of the fringing plain. The glacier is partly concealed by a rock of the foreground. From a photograph by J. J. McArthur, 1894. See page 6.

The depth of the moraine, or moraine-delta, where it occupies the middle of the fiord is more than 500 feet. The profile of the ice fan, as shown by photographs, has a slope of one foot in ten (see fig. 4). The gravel lowland is much flatter, but the submerged face of the deposit descends to the bottom of the fiord with a general rate of one foot in three.

We made no landing here, and our facts are derived chiefly from Russell, who visited the foot of the glacier in 1889; from the Coast Survey chart, based on surveys in 1890–94; and from photographs made by the Canadian

Boundary Commission in 1894.[1] They are of interest in this connection chiefly from their bearing on the interpretation of morainic ridges observed farther west, at the front

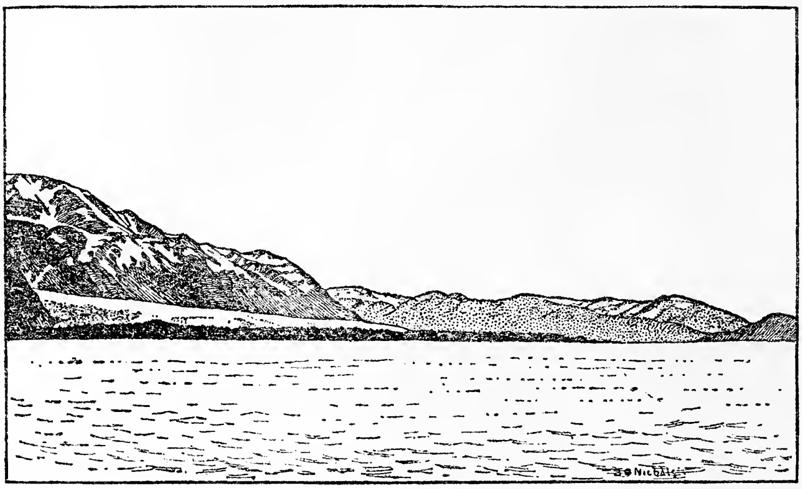


FIG. 4. DAVIDSON GLACIER.
Side view of expanded end, June, 1899.

of the Fairweather Range. If Davidson Glacier were to melt away and the sea to retreat from Chilkat Inlet, there would remain in the valley a high ridge of water-laid gravel, recording by its circling course the present outline of the glacier front, and by its even crest line the present position of the sea surface.

As to modern changes in the extent of this glacier there is little specific information, but the condition of the fringing plain warrants a few general statements. An outer zone is covered by forest, an inner is barren (figs. 2, 3 and 5). The forest is in general lofty, dense, and apparently mature, but a narrow belt next the barren zone has smaller trees in rather open growth. The forest zone has an average width of less than half a mile, ranging from one-fourth at the north to five-eighths at the south; the bar-

[1] See page 6 and figs. 2 and 3.

ren zone in 1894 ranged from one-fourth mile (east side) to nearly one-half mile (north side). There were many lakelets in the barren zone (1894) and a few in the forest,

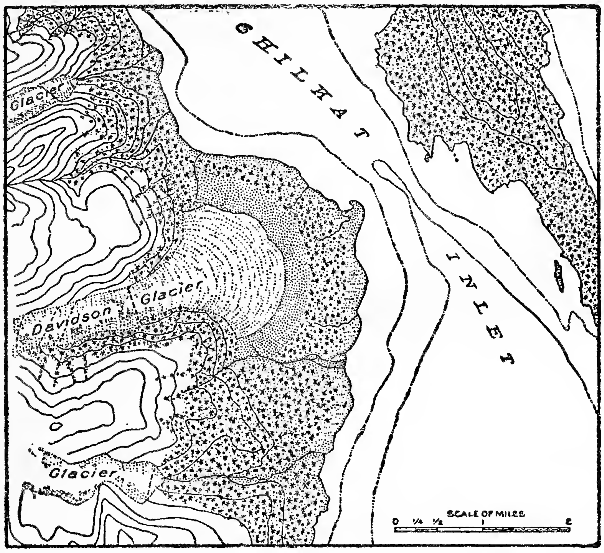


FIG. 5. MAP OF LOWER PART OF DAVIDSON GLACIER.

Based on Coast Survey chart 8303 and Boundary Commission photographs made in 1894. The contour interval on land is 500 feet; under water, 250 feet. Barren lowlands dotted; forest indicated by stars.

and these are probably indicative of the melting of ice buried under the gravel. It seems safe to infer (1) that for centuries (age of the mature forest) the glacier has not exceeded its present extent by more than three-eighths of a mile, and (2) that the period since it last

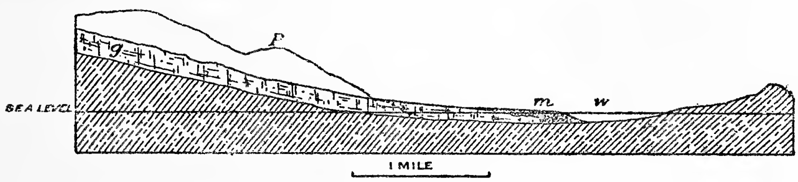


FIG. 6. LONGITUDINAL SECTION OF DAVIDSON GLACIER AND CROSS SECTION OF CHILKAT INLET.

g, glacier. *m*, moraine-delta. *w*, water of inlet. *p*, profile of mountain range near glacier.

reached the three-eighth-mile limit is roughly measured by the age of a half-grown forest.

GLACIER BAY

The next depression west of Lynn Canal is broader, as well as more complex in the details of its configuration, and its general trend is northwestward instead of northward. On the west it is separated from the Gulf of Alaska by the Fairweather Range, the dominant mountain mass of this region. Glacier Bay, occupying its main axis, sends many branches into the troughs among its hills and mountains, and would be still more complicated in outline but for the clogging of the valleys by glaciers. Six of its inlets head against ice walls, from which bergs are constantly falling.

The glaciers of this basin are better known to the physical geographer than any others of the Alaska belt, and one of their number, the Muir, enjoys the same preeminence in popular acquaintance and appreciation. The group was explored, sketched, and studied by Muir in 1879 and 1880. Wright made a visit in 1886, producing a rough map and working out the main elements of the later glacial history. Reid, in 1890 and 1892, executed a careful survey of the shores, the lower portions of the tidal glaciers, and a broad inland tract including the greater part of Muir Glacier; developed much further the history of recent changes; and instituted a number of investigations bearing on the physics of glaciers. Minor studies were made by Cushing (1890) and Russell (1890), the map work has been extended by the Canadian Boundary Commission, and a fine series of photographs were made by the Commission in the summer of 1894.

To the body of information gathered and published by these investigators[1] our addition was comparatively unimportant. The five long days of our stay, though utilized to the utmost and replete with interest, served only for a partial review of the features of the immediate coast. As to the more general aspects of the topography and physical history we verified the work of our predecessors, but we were able to extend it only by bringing down to date the records of changing glacier fronts.

Except near the mouth, the shores of Glacier Bay are treeless, and large tracts are almost destitute of vegetation. A variety of other facts show that this barrenness is due to the recent occupation of the surface by ice, and the extent of the barren zone measures the amount of modern recession of the glaciers. Another series of phenomena, including vestiges of a forest and remnants of a moraine-delta, show that the epoch of expanded glaciers was preceded by an epoch of contracted glaciers when the ice occupied less space than at present. Thus, from a condition of minimum extent, the glaciers grew to a maximum of brief duration and then wasted away to their present dimensions. Vancouver's narrative seems to show that at the time of his visit to the coast (1794) the ice was near its maximum, and subsequent observations, beginning with those of Muir in 1879, show rapid and nearly continuous retreat. The magnitude of this oscillation is perhaps without parallel in the records of glacial changes within the historic period. During the maximum epoch an ice flood not only filled Glacier Bay for thirty-five or forty miles, but submerged many islands and bordering hills

[1] John Muir, Cruise of the Corwin in the Arctic Ocean, p. 136, 1884; The Mountains of California, pp. 23–24, 1894. H. F. Reid, Nat. Geog. Mag., vol. IV, 1892; Sixteenth Ann. Rept. U. S. Geol. Survey, part I, 1896. H. P. Cushing, Am. Geol., October, 1891. G. F. Wright, Am. Jour. Sci., Jan., 1887; The Ice Age in North America; Man and the Glacial Period. I. C. Russell, Am. Geol., March, 1892.

from 1,000 to 2,000 feet in height and reduced the lesser mountains of the basin to the condition of projecting peaks, or nunataks. The sea front made a continuous ice cliff ten miles long. Then the great trunk glacier gradually wasted; the rounded crests of submerged hills began to reappear as nunataks; rows of nunataks coalesced into mountain ranges; the ice cliff retreated up the bay, passing one nunatak after another and leaving it as an island or a promontory; one by one the tributary ice streams were abandoned by the waning trunk and left as independent glaciers, whose terminal ice cliffs retreated gradually up their several sea arms. These modifications of the coastal geography were accompanied by equally remarkable changes at higher levels. Several glaciers lost their névés, by dissipation or by diversion, and being thus deprived of nourishment and of part of their propelling force, lie nearly stagnant and are slowly melting away. A number of fragments of ice streams are stranded on flat passes among the hills, where they lie almost inert but

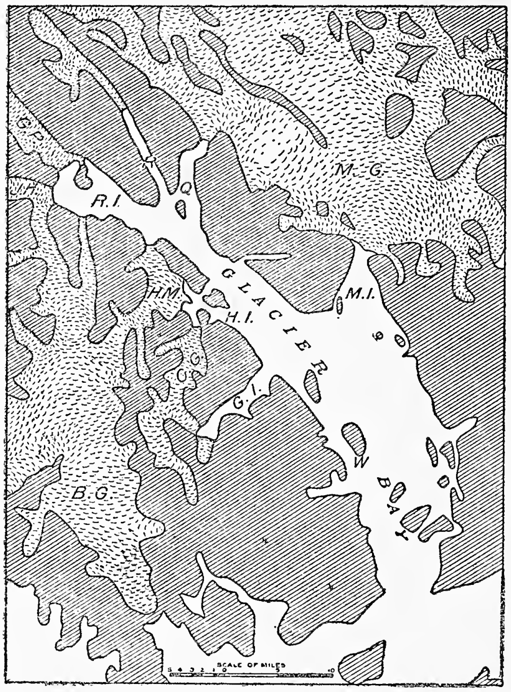


FIG. 7. MAP OF GLACIER BAY.

Ruled areas, land. *BG*, Brady Glacier. *CG*, Charpentier Glacier. *GI*, Geikie Inlet. *GP*, Grand Pacific Glacier. *HI*, Hugh Miller Inlet. *HM*, Hugh Miller Glacier. *JH*, Johns Hopkins Glacier. *MI*, Muir Inlet. *MG*, Muir Glacier. *Q*, Queen Inlet. *R*, Rendu Inlet. *RI*, Reid Inlet. *W*, Willoughby Island.

with slow movement on two sides in opposite directions, part of the mass tending backward toward its original source.

Of the abundant evidence from which this history was worked out by my predecessors[1] I saw only a small fraction, but enough to substantiate their conclusions in all essential respects. I skirted the barren coasts over which vegetation is slowly creeping from the south. I saw glacial till and gravel charged with bruised trunks and boughs from the ancient forest. I saw the bare ice-carved hills, still retaining striæ and polish under a climate that has obliterated from most exposed surfaces the similar records of Pleistocene glaciation (pl. XVIII). I saw the banks of stratified gravel before Muir Glacier — remnants of the old moraine-delta — and noted that their upper surface had been first sculptured by the readvancing glacier and then sheeted with till during the subsequent retreat. And I saw a remnant of the ice flood stranded on a saddle a thousand feet above tide.

The saddle to which I refer is part of a small trough extending southeast from Hugh Miller Inlet and lying parallel to the adjacent great trough of Glacier Bay. During the recent ice maximum an ice current followed this trough from northwest to southeast, and when the supply from the northwest finally ceased and this strand of ice had nothing to urge it except its own weight, its ends slid into neighboring valleys, but the central part lay balanced on the summit and became stagnant (fig. 8). The adjacent hills are too low to furnish the snow needed to replenish its annual loss by melting, and so it is slowly wasting away

[1] Wright, Am. Jour. Sci., 3d series, vol. XXXIII, pp. 11–18, 1887; Ice Age, pp. 55–62, 1889. Reid, Bull. Geol. Soc. Am., vol. 4, pp. 32–41, 1893; Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, pp. 434–442, 1896. Cushing, Am. Geol., vol. VIII, pp. 214–224, 1891.

Of the existing glaciers of the basin ten are now tidal. We visited the Muir, Reid, and Hugh Miller. To the Grand Pacific, Johns Hopkins, and Charpentier we approached so near as to obtain some information as to re-

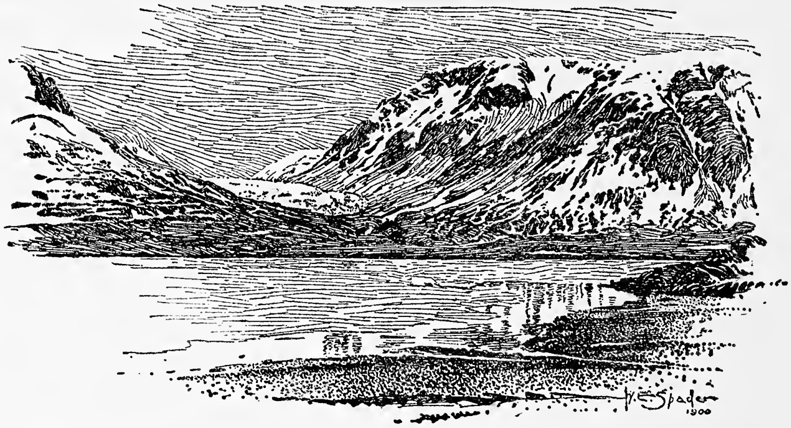


FIG. 8. REMNANT GLACIER SOUTH OF HUGH MILLER INLET, FROM A PENINSULA IN THE INLET.

The ice mass occupies a typical glacial trough, shaped by an ice current flowing southeastward, or from the observer. Photographed June 10, 1899.

cent changes. Of the Carroll, Rendu, Geikie, and Wood we had only distant views.

Muir Glacier. — The Muir Glacier is not only the largest of the group but the most accessible. It has been

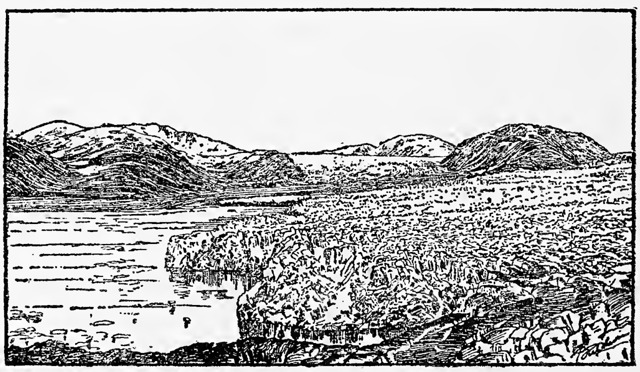


FIG. 9. MUIR GLACIER.

Photographed June 9, 1899, from point on mountain spur at the east, a little lower than point *E*, fig. 10.

visited by many ship-loads of tourists; it has received the chief attention of students of physical geography; and much is known of its recent history. Muir's notes and sketches record the approximate position of its sea cliff in 1880, and photographic and instrumental determinations of its outline were made by Wright in 1886, and by Reid

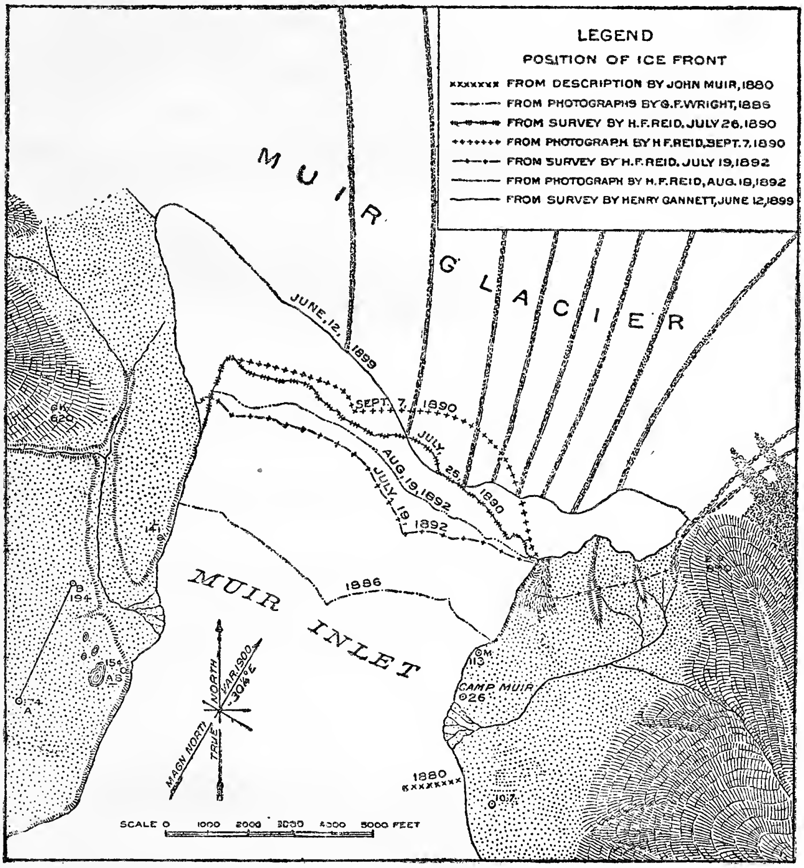


FIG. 10. MAP OF NORTHERN PART OF MUIR INLET.

Showing position of front of Muir Glacier at various dates. Reid's survey stations are indicated each by a letter, dot and circle, with figures showing height in feet above mean tide. *A* and *B* were the extremities of his base line.

in 1890 and 1892. During our visit the outline was mapped by Gannett, who tied his work to monuments left

by Reid. The accompanying map (fig. 10) is copied from Reid, with the addition of Gannett's line showing the condition on June 10–12, 1899.[1]

From 1880 to 1886 the cliff retreated about 4,000 feet; from 1886 to 1890, 3,300 feet. Between 1890 and 1892 there was an advance of 700 feet; between 1892 and 1899 a retreat of about 1,900 feet, nearly the whole of the change occurring after 1894. The net retreat in nineteen years was 8,500 feet, or 1.6 miles.

Although several of these surveys were quite accurate, I have stated their results in round numbers, because greater refinement would tend to mislead. The forward flow of the glacier probably varies little from day to day, but the breaking away of the cliff is quite irregular and the outline of the front continually changes. Besides this change in local detail there is a general change of more permanent character, to be described presently; and it is probable that an important seasonal oscillation interferes with the direct comparison of observations made at different times of year. The average annual retreat of the ice cliff for the four years preceding 1890 was 800 feet, and for the following two years the average advance was 350 feet; but Reid noted in the summer of 1890 a retreat of 500 feet in 43 days (July 26–September 7), equivalent to an annual rate of 4,000 feet. Again in 1892 he made two observations 31 days apart (July 19–August 19), and these show retreat at the rate of about 3,500 feet per annum; but the whole retreat in the seven following years

[1] Reid's map is pl. xcv*a* in 16th Ann. Rept., U. S. Geol. Surv., Part 1, 1892. Gannett's work was limited to the changed ice front and the resulting extension of the shore line. Field notes and photographs show that there were associated changes in the drainage of the gravel plains, but as these data are not sufficient for the correct delineation of the streams in 1899 I have left them as Reid represented them. Some time before 1894 the northern branch of the western creek found a shorter course to the inlet, reaching tide about three-fourths of a mile nearer the glacier; and some time between 1894 and 1899 a similar change occurred on the east side of the inlet.

was only 1,900 feet. It is therefore probable that the summer rate of retreat is much more rapid than the winter.

While these considerations tend to qualify the figures deduced from uncorrected observations, they do not affect their general tenor. The application of a correction for seasonal oscillation would diminish by a few hundred feet the estimate for the total retreat from 1886 to 1890, and increase by a similar amount the estimate for the total retreat from 1892 to 1899, but would leave unchanged the general result that the retreat in nineteen years has been more than a mile and a half, and that the general retreat suffered at least one interruption, a small advance occurring between 1890 and 1892.

The general change of contour mentioned above is of peculiar interest because it was predicted by Reid. The middle of the glacier ends in deep water, a maximum sounding of 720 feet having been recorded, but at each side of the rock trough the ice rests on a bank of gravel rising above the water level. Observing that the surfaces of these gravel banks descend northward beneath the glacier, Reid inferred that with the progress of recession lanes of sea water would soon be admitted between the ice and the gravel; and having determined that the marginal parts of the glacier advance very slowly as compared to the medial, he inferred that their cliffs would be carried back with relative rapidity by the attack of the warm sea water. As the map shows, these expectations have been fully realized.

In bringing the record of the glacier down to the summer of 1899 the preceding paragraphs practically close a division of its modern history, for a new epoch was introduced only three months after our visit. On the 12th of September the southern coast of Alaska was shaken by a severe earthquake, and other shocks followed at intervals. These greatly modified the condition of its tidal glaciers,

and the Muir, at least, has not yet, after the lapse of three years, resumed its normal habit. Just what changes were made we do not know, because ordinary sources of information have been cut off and no student of glaciers has yet made an investigation.

On July 29, 1900, O. H. Tittmann, Commissioner for the United States on the International Boundary, visited Glacier Bay on the tourist steamer 'Queen.' In the lower part of the bay the main channel was so obstructed by floating ice that the commander of the vessel sought for an easier passage west of Willoughby Island, and finally desisted from the attempt to approach the glacier when opposite the mouth of Muir Inlet. Looking ahead it appeared to Tittmann that the whole of Muir Inlet was occupied by an ice pack, the ice being probably grounded and stationary. Instead of being able to steam as usual to the very front of the glacier, the vessel was turned back at a point about ten miles distant. In the summer of 1901 tourist steamers were stopped by the pack at distances from the glacier ranging from five or six to eight or ten miles. In December of the same year a special trip was made by the 'City of Topeka,' for the purpose of forecasting the accessibility of the glacier for the excursion season of 1902. The way was then found comparatively open, and the steamer approached within about a mile of the glacier; but in the following summer the nearest approach was to a point five or six miles distant.

These facts seem to show that the earthquake shock, or shocks, not only set free a great quantity of ice, including bergs of unusual size, but left the glacier in such condition that bergs were more easily detached in subsequent years. The determination of the nature of that condition will be of much interest to students of the physics of glaciers. Joint systems in rock have been plausibly ascribed to the passage of earthquake waves, and it is easy

to understand that the comparatively weak and equally brittle material of glaciers may be still more susceptible to rupture by sudden strain. As the tension cracks incidental to the flow of glaciers are quickly welded, except near the surface, it would appear probable that earthquake cracks in the terrestrial parts of a glacier have no permanent effect of importance, but the case may be materially different in the parts encroaching on the sea.

As heretofore known, the frontal wasting of Muir Glacier has been chiefly by melting below the water-line, and the ordinary bergs, produced by the shearing off of the overhanging upper portion, have been of moderate size, readily floating away. The greater bergs which stranded in the inlet after the earthquake may have been produced by cracks which divided the glacier from top to bottom.

Reid Inlet. — Glacier Bay parts at its head into three branches (fig. 7). The westermost division, Reid Inlet, receives the Grand Pacific Glacier from the northwest, the Johns Hopkins from the west, and the Reid from the south, the three fronts circling in compact order about the western or northwestern end of the inlet. In 1899 (as also in 1892) this was the region of most active berg formation, and on the day of our visit, June 12, the floating ice was packed so closely as to stop our progress — with a rowboat — and we succeeded in reaching only the Reid Glacier. With the use of a plane-table, a map was made of the lower end of Reid Glacier, and imperfect topographic sketches of the ends of the Johns Hopkins and Grand Pacific; and the data thus obtained were afterwards combined with the representations of the same district by Reid[1] and the Canadian Boundary Commission to produce the sketch map in fig. 11.[2]

[1] Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, pl. LXXXVI, 1896.

[2] There is some confusion as to names of glaciers about the upper part of Glacier Bay. Muir, the explorer of the region, gave manuscript names, some

In the original exploration of Reid Inlet in 1879, Muir found it headed by a single great glacier whose ice cliff spanned the fiord from wall to wall, being interrupted only by a single boss of rock, half island, half nunatak. This glacier he named the Grand Pacific. When Reid in 1892 found and mapped two great glaciers, besides a third of moderate size, Muir wondered and was perplexed, for it did not seem possible that he could have overlooked two tidal glaciers; and it was not until he revisited the inlet in 1899 that the mystery was solved. During the thirteen years which had intervened between exploration and sur-

of which received newspaper publication. Reid, who made the first survey (1892), adopted Muir's names and added others, his nomenclature being first fully published in 1896 (Sixteenth Ann. Rept. U. S. Geol. Survey; text and map). The Canadian International Boundary Commission, surveying the same region in 1894, prepared maps with a different nomenclature. These maps, being primarily for the use of commissioners in connection with the pending boundary question, have not been officially published, but they have been unofficially distributed and their data compiled in various maps.

The following are the discrepancies:

	Reid's name.	*Can. B. Com. name.*
Glacier reaching Reid Inlet from the north.	Grand Pacific.	Johns Hopkins.
Glacier reaching Reid Inlet from the west.	Johns Hopkins.	No name.
Glacier reaching Rendu Inlet.	Rendu.	Charpentier.
Glacier reaching Hugh Miller Inlet from the south.	Charpentier.	No name.
Glacier reaching Queen Inlet.	Carroll.	Woods.
Glacier reaching Geikie Inlet from the south.	Wood.	No name.

It would appear that the cartographer of the Commission had moved three names—Johns Hopkins, Charpentier, Wood(s)—from the glaciers to which they were attached by Reid, and given them to other glaciers, displacing the names given to these others by Reid. No new names are added, and the displaced names do not appear elsewhere.

Reid's nomenclature is followed by the U. S. Coast Survey in chart 3095, Glacier Bay (1899). The Canadian Commission is followed by the U. S. Coast Survey in chart 8001, Northwestern coast of North America (edition of 1898), and in chart 3091, Territory of Alaska, southeast section (1898). Otto J. Klotz, an officer of the Canadian Survey, in the Geographical Journal (vol. XIV, 1899), uses Reid's name, Grand Pacific, in his text (p. 529), but in the titles to two figures (pp. 527, 529) applies the Commission name Johns Hopkins to the Grand Pacific Glacier of Reid.

Reid's names have recently been adopted by the U. S. Board on Geographic Names. See National Geographic Magazine, vol. XII, page 87, 1902.

vey the main trunk of the Grand Pacific had disappeared, leaving three of its branches as independent tidal glaciers. The name has been retained for the northwestern branch. In 1894 the district was resurveyed by the Canadian Boundary Commission, and another record was made of the progressive changes of the glaciers.

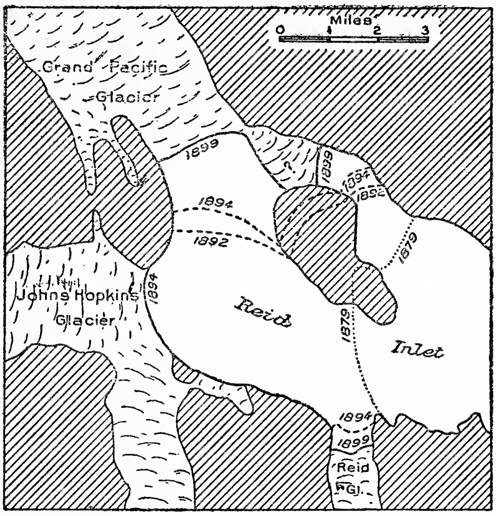


FIG. II. MAP OF HEAD OF REID INLET.

Showing positions of ice front in different years. Land areas are ruled.

The Grand Pacific in 1892 and 1894, as in 1879, presented two fronts to the waters of the inlet, the fronts being separated by a high rock island, but in the later years a much larger part of the island was laid bare. In 1899—as nearly as my distant views enabled me to determine—the western and greater arm of the inlet had eaten back into the glacier so as to reach some distance beyond the head of the island and approach the mainland at the northeast, thus isolating a body of ice lying between the island and the mainland. The arrangement of moraines delineated by the Boundary Commission showed that in 1894 this body had ceased to be replenished by the current of the Grand Pacific, so that its complete wasting was a mere question of time.[1] It is possible that in 1899 it had become so far reduced as no longer to touch the island.

[1] These moraines are beautifully shown in one of the Commission's photographs: A. J. Brabazon, No. 45, vol. 14, p. 13.

The front of Johns Hopkins Glacier has suffered less change since Reid mapped it, but there has been some retreat. A comparison of photographs made in 1892 and 1899 shows that more rock is exposed at the south; and a remnant of ice I could see clinging to the mountain side at the north showed that the front had within a very few years held a position several hundred yards more advanced than in 1899. Its determined changes were so small that no attempt has been made to express them in the accompanying diagram.

The remaining glacier of the three was indicated in a general way on Reid's map of 1892, but its lower end was represented by a dotted line, implying doubt as to its precise position, and no name was attached. It was more confidently delineated by the Boundary Commission in 1894. As my map and photographs give such determination of the position of its ice cliff that future changes can be measured, it seemed proper to supply Reid's omission in respect to name, and the Harriman Expedition adopted the name Reid. I am glad to be able to illustrate somewhat fully a feature bearing a name so deserving of honor in Alaska glaciology.

FIG. 12. REID GLACIER; DISTANT VIEW FROM THE NORTH IN 1894.
From a photograph by A. J. Brabazon.

As already mentioned, the Reid Glacier was a branch of the Grand Pacific in 1879, but not many years could have elapsed before the recession of the latter made it independent, and it is probable that its end then projected somewhat beyond the general line of the south wall of the

inlet. One of Reid's photographs shows that in 1892 it had retired within the general line of the mountain front. The Boundary Commission's map places it outside the position of Reid's dotted line; and in 1899 it was a half mile within the limiting capes. A comparison of the Commission's photographs[1] with my own indicates a recession of about 1,500 feet in five years, accompanied by an important modification of the character of the front. The removed portion was part of an ice cascade, and as there was little change in the thickness of the glacier, the terminal cliff in 1894 was much lower than in 1899.

FIG. 13. REID GLACIER; DISTANT VIEW FROM THE NORTHEAST IN 1894.
From a photograph by A. J. Brabazon.

I found three masses of dead ice, testifying to the former greater extent of the glacier. One of these masses rested on a small promontory just east of the glacier front. A knob of marble is connected with the main mountain by a comparatively low saddle, and on this saddle lay a body of ice apparently several scores of feet in depth but almost wholly concealed by stones and gravel. This was outside the line of flow of Reid Glacier, and could only be a remnant of the mass of the Grand Pacific when that glacier occupied the full width of the inlet. It dated back to a time when the conditions were as observed by Muir in 1879, and its gradual melting had probably been in

[1] Especially A. J. Brabazon's No. 38, vol. 14, p. 11.

FIG. 14. REID GLACIER, FROM THE NORTHWEST, JUNE 12, 1899.

Figs. 14 and 15 are companions, showing the same bay and ice cliff from opposite sides of the bay. The length of the cliff was 4,260 feet, and its height ranged from 200 to 250 feet. The upper end of the glacier, and the summits of the bordering mountains were concealed by cloud. In the foreground at the right is a snow-covered talus of the western valley wall, probably resting in part on stagnant ice. The dark mass in middle foreground is part of the moving glacier, heavily charged at the surface with rock débris.

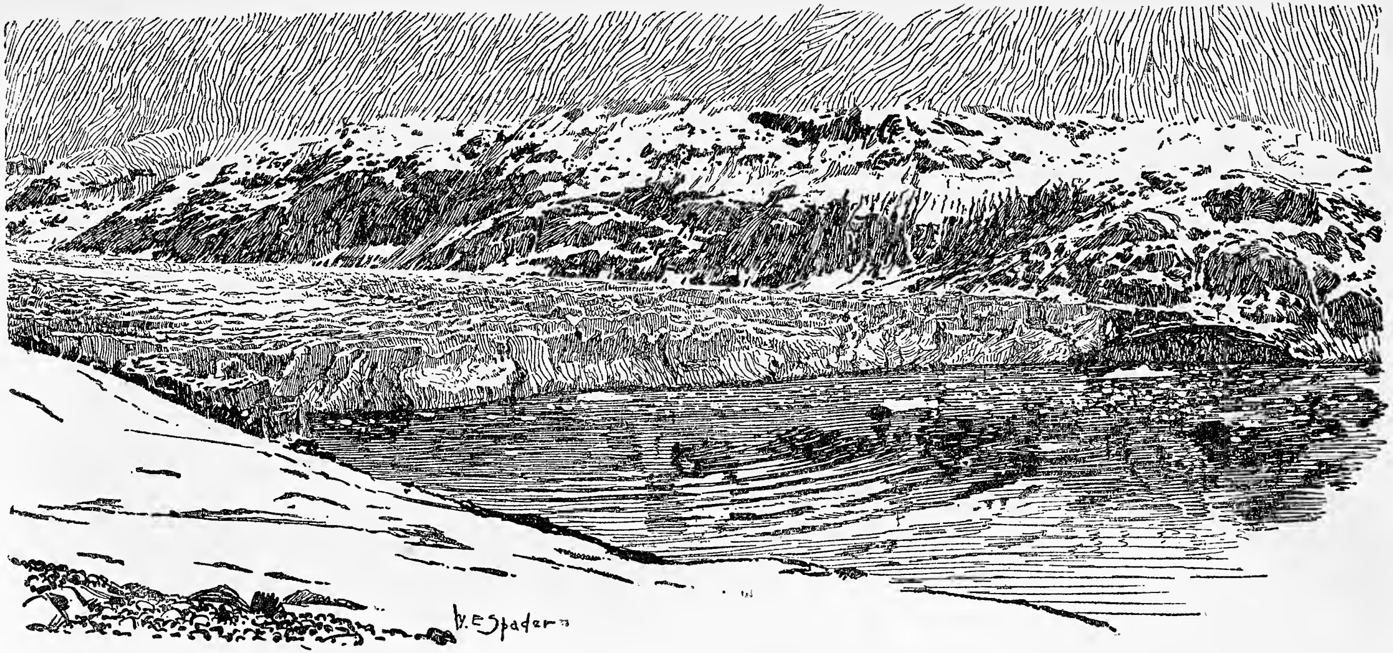


FIG. 15. REID GLACIER, FROM THE NORTHEAST, JUNE 12, 1899.

Companion view to fig. 14. An iceberg had parted from the cliff not long before and the circling waves its fall set in motion were caught by the camera. A dark mass adjoining the white ice cliff at the right is a remnant of the glacier which has ceased to move and is slowly wasting. The snow-bank of the foreground at the left covers a stagnant ice remnant belonging to an earlier stage of the local glacial history (page 29).

progress for nearly twenty years. The other masses clung to the walls of the trough occupied by Reid Glacier, and were still continuous with the ice of the glacier, although they had ceased to move. They were simply portions of the retreating glacier so well supported by the land that they had not fallen into the sea when the deeper parts of the ice stream were melted. They were partly covered by gravel and other rock débris, but still showed faces of white ice near their junction with the glacier. That on the west side extended about 1,200 feet beyond the general ice front, and the eastern mass was nearly or quite as long. From these remnants it is inferred that there was a somewhat gradual shrinkage of the glacier after the record of 1894, and that it did not immediately assume the proportions observed in 1899.

The width of the Reid at its débouchure is seven-eighths of a mile, and the general height of its ice cliff about 100 feet. The frequent falling of ice masses during our visit gave the impression that it was discharging bergs rapidly, but the little bay before it carried less floating ice than the open inlet beyond.

The data compiled in the map of the inlet (fig. 11) are of unequal precision. The line representing the ice front in 1879 depends largely on the recollection of Muir, but his recollection is supported by notes and a landscape sketch made at the time. The fronts of Grand Pacific Glacier in 1892 and 1894 are believed to be close approximations, but the front in 1899 has much less authority and may involve considerable error.

The total retreat along the axis of Johns Hopkins Glacier in the twenty years preceding 1899 was about three and a half miles, and the retreat of the Grand Pacific along the line of its western distributary was three and a half to four miles in the same period. Reid Glacier retreated a half mile after its separation, the period being some-

thing less than twenty years. In 1879 the Grand Pacific had a total water front of over three miles; in 1892 and 1894 the separated glaciers presented a total front of more than six miles, the exposure to the sea being progressively increased up to that time. Afterward the length of front underwent little change, and should recession continue it will diminish. Unless the enlargement of the ice front was compensated by shoaling of the water, the sea had exceptional advantage for twenty years in its attack upon the ice, and this advantage may have been connected with the phenomenal rate of recession.

Bergs.— The upper part of Reid Inlet in 1899 not only contained more floating ice than any other portion of Glacier Bay, but its bergs were of greater size than any others we saw. The one pictured in fig. 16 was ascer-

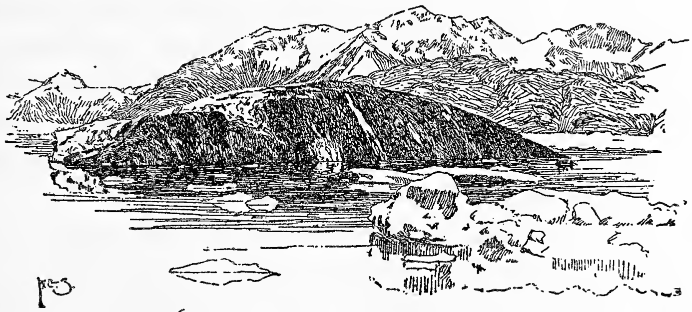


FIG. 16. ROCK-LADEN BERG IN REID INLET.

Scale is given by a boat. The nearer face of the berg, black with embedded detritus, is probably part of the base of the parent glacier. Photographed June, 1899.

tained to rise 76 feet above the water, and one of my companions who landed upon it and walked from end to end, estimated its length by pacing at 750 feet. Having my eye gaged by these measurements, I was able to form an approximate judgment of the size of other large bergs seen; and I estimated the largest, which was approximately tabular and square in form, to measure 1,000 feet on each side and to rise 100 feet from the water. The thickness was probably not less than 500 feet. These

dimensions raised questions as to the mode of calving. Reid, from studies of the Muir, inferred that waste along the ice front was chiefly from melting by sea water; and this melting, in combination with the forward flow of the ice, produced an overhang, resulting in the breaking away of the upper portion of the glacier by its own weight. Such observations as I was able to make at various ice cliffs were in full accord with his view, and the great bergs of Reid Inlet may perhaps have been formed in that way; but their size led me to wonder whether another process might not be involved. Many of the immense bergs of the Antarctic Ocean are tabular in form, and it is believed that they have the full thickness of the parent glaciers, which were protruded into the sea until actually floating upon its surface before the separation took place. In order that the Grand Pacific or the Johns Hopkins should produce bergs of this type, it would be necessary that the depth of the fiord in front of the ice cliff should be not less than seven-eighths the thickness of the glacier.

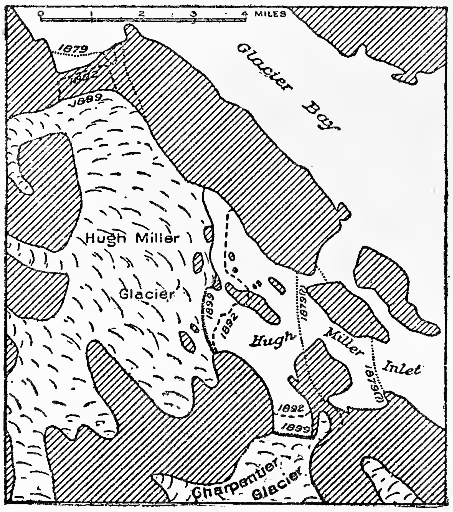


FIG. 17. MAP OF HUGH MILLER INLET.

Showing positions of the ice front in different years. Land areas are ruled.

Hugh Miller Inlet.—Hugh Miller Inlet occupies an irregular recess among the hills and mountains on the southwest side of Glacier Bay. Rocky islands of moderate elevation half block its entrance and interrupt its surface. Charpentier Glacier reaches it from the south, terminating in a low ice cliff about seven-eighths of a mile

broad. The Hugh Miller, descending from the mountains at the southwest, spreads into a broad field northwest of it, and has a double discharge, one part coming eastward to the inlet, and the other going northward toward Glacier Bay. The face toward the inlet is about three and a half miles long. The southern third overlooks the water in a low cliff, and the remainder presents a sloping surface black with accumulated rock débris. Though the land-locked inlet gives the floating ice scant opportunity to escape to the open bay, very little was accumulated at the time of our visit, June 11, and all the bergs were small.

FIG. 18. TILL LEFT BY HUGH MILLER GLACIER BETWEEN 1880 AND 1890.

Photographed in 1899. The till is thin, but contains remnants of ice, and was englacial in part. The single bush visible, almost the only vegetation on the new ground, is a willow.

The dates of exploration and survey are the same as for Reid Inlet and the general history of change is strictly parallel. Muir observed but a single glacier, to which he gave the name Hugh Miller. Reid found two, and added the name Charpentier. With the aid of Reid's map I was able to indicate somewhat definitely the extent of the subsequent recession, and Muir, in revisiting the locality with

me, was able to say that the change previous to Reid's survey was greater in amount than the more recent modification.

But after the lapse of twenty years Muir found it impossible to recall the precise position of the ice front in 1879, and a subsequent study of his notes and sketches left the matter still in doubt. On the accompanying map (fig. 17) I have drawn two tentative lines, one crossing the inlet near its mouth, the other running northward from the peninsula which margins the Charpentier Glacier. The more conservative of these implies that the face of Hugh Miller Glacier retreated about one and a half miles between 1879 and 1892.

In 1892 Charpentier Glacier had two fronts, separated by its contact with a broad rock island or peninsula. One front, facing northward, was tidal; the other, facing northeastward, was non-tidal, but ended close by the water.

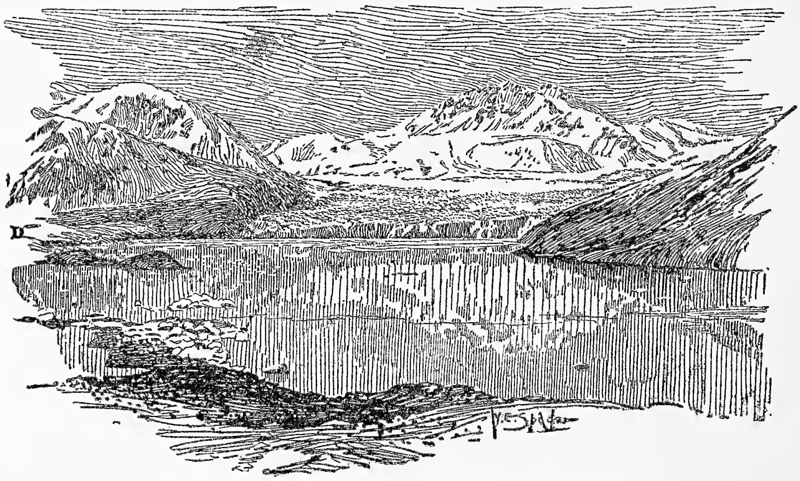


FIG. 19. CHARPENTIER GLACIER IN JUNE, 1899.

Its surface was dark from the accumulation of rock débris, and its motion had probably ceased. Seven years later the tide-water front had retreated about one-third of a mile, thereby nearly severing its connection with the inert mass at the northeast (*D*, fig. 19), and the waste of the latter

EXPLANATION OF PLATE III

Hugh Miller Glacier

The glacier flows to Hugh Miller Inlet, Glacier Bay, from the west. See figure 17.

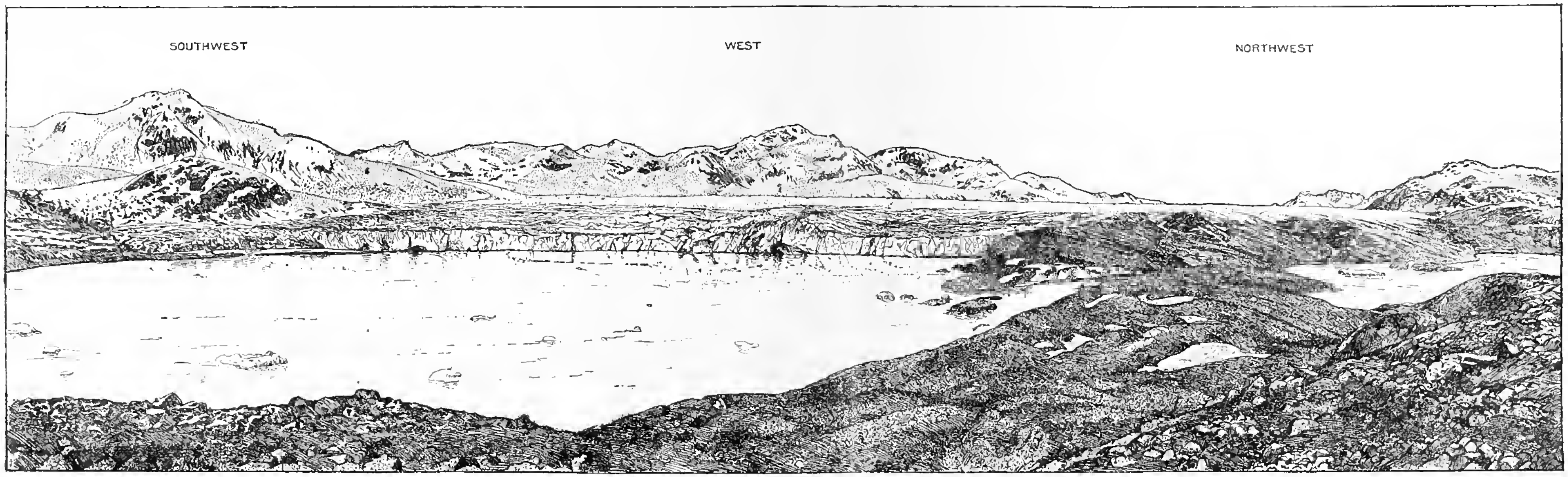
The panoramic photographs reproduced in this view were taken from the summit of an island.

The main névé feeding the glacier lies to the left of the view, and the ice stream from it flows beyond the peak seen at the southwest, first coming into view in the west-southwest. It then spreads broadly, and flows down a valley to the northwest as well as toward the observer.

The ice cliff bordering the broader stretch of water is nearly a mile long and from 100 to 140 feet high. A cave mouth at the left marks the issue of a stream flowing through a tunnel in the ice.

See pages 34–38.

Drawing by S. B. Nichols, from photographs made by G. K. Gilbert, June 11, 1899. Negatives nos. 265, 266, 267 and 268, United States Geological Survey.



HUGH MILLER GLACIER

PANORAMIC VIEW FROM AN ISLAND IN HUGH MILLER INLET. PHOTOGRAPHED IN JUNE, 1899

had progressed so far as to render its surface almost black from the accumulation of residuary moraine stuff. These relations are indicated in figure 17. The condition in 1894 was intermediate between those of 1892 and 1899. A comparison of Reid's photographs and mine shows also that the Charpentier had lost in thickness as well as area, the lowering near its front being estimated at about fifty feet.

As mapped and described by Reid, Hugh Miller Glacier rested at one point against an island, and only the portion south of the island yielded bergs. The northern division of the front descended to tide-water, but was covered at its margin by débris and had no cliff. In 1899 the front had retreated so as to open a narrow channel west of the island and expose the top of another island on which a tongue of the ice rested. South of this point the ice cliff had retreated westward to an average distance of 1,000 feet, the maximum being nearly 2,000 feet. It still yielded bergs, but sparingly, and was probably approaching a non-tidal condition. A large nunatak at the south, which was mapped and photographed by Reid, was more fully exposed than before, and a small one had appeared between it and the ice cliff. Near the northern end of the cliff the distortion of dirt bands and an uprising of the surface of the ice suggested that another rocky islet would soon be exposed. The retreat of the northern portion of the glacier face had laid bare a group of rocks projecting slightly above the water, and a larger rock knoll was gradually emerging. At one point it projected as a nunatak about 150 feet above water-level, and farther on was revealed at the water's edge. The average width of the space here abandoned by the ice is about 1,500 feet. (See pl. III.) The condition in 1894, as indicated by photographs, was intermediate, but nearer to the condition in 1899 than to that in 1892.

At the northern margin of the Hugh Miller ice field, where it discharges toward Glacier Bay, there is somewhat similar evidence of retreat. Muir's sketch shows that this front reached tide-water in 1879, but was interrupted near its eastern margin by a small island. This detail serves to fix its approximate position as represented in fig. 17. Reid states that at the time of his survey it was non-tidal, but his map places the ice margin at the water's edge. Photographs made in 1894 indicate a bare tract 1,500 or 2,000 feet broad between the ice front and the strand, and at the time of my visit the distance was 2,600 feet, the surface being chiefly occupied by ground moraine. The ice front in 1899 had a gradual slope, was covered by drift near its margin, and was traversed by a large medial moraine. Close to its front it received a tributary, cascading down a narrow valley from the west. The total retreat of the ice front at this point was probably a little less than one mile in twenty years.

Geikie Inlet. — Exploring Geikie Inlet in 1879, Muir found it headed by a tidal glacier, to which he gave the name Geikie. His notes estimate its width as several miles, but do not serve to fix the position of its front. In 1892 Reid found that its front had receded so far as to convert its two branches into distinct glaciers. Retaining the name Geikie for the more northerly, he called the other Wood Glacier. The Geikie was tidal; the Wood barely touched the water at two points, but yielded no bergs; and the nearer corners of the glaciers were connected by a short body of motionless ice. Photographs made by the Canadian Boundary Commission in 1894[1] show that in the two years elapsed since Reid's survey both glaciers had shrunk, the Wood receding several hundred feet and the Geikie about half a mile. The

[1] A. J. Brabazon, Nos. 32, 38, 39 and 40, contained in volume 14 of the official album, pp. 9, 32 and 33.

Geikie was still tidal. The two were still connected by stagnant ice, a long, narrow strip, partly protected from melting by moraine stuff. In 1899 we failed to reach the head of the inlet, so that my only contribution to its history consists in assembling the observations of others.

LA PEROUSE GLACIER

Fairweather Range, which bounds Glacier Bay on the southwest, presents its other face to the open ocean. Its seaward face is bold and lofty, and the greater part of it is above the snow-line. While rugged in detail it is little complicated by foothill ranges, and from the ship's deck we could trace a number of its long glaciers from end to end. Between its base and the sea there is usually a narrow foreland, but this disappears toward the east and broadens toward the west. At several points it gathers the alpine glaciers into massive piedmont sheets, and several of these approach or actually touch the sea. The La Perouse, at whose edge we made a landing, is of this type, being fed by alpine glaciers from the slopes of the range about Mounts Crillon, D'Agelet and La Perouse.

FIG. 20. LA PEROUSE GLACIER, 1899.

Showing the alpine glaciers that feed the plateau mass below; and the relation of the timbered ridge at the left.

Its extent in the direction of the coast is about three miles, the central portion ending in a lofty white cliff. The eastern third is darkened by a covering of moraine and appears to be separated from the water by a strand.

The western part is partly concealed by a timbered ridge running parallel to the coast (fig. 20). This ridge, which is probably a huge moraine of Pleistocene age, extends westward far beyond the end of the glacier. Our landing (June 18) was at the western end of the ice cliff, coinciding with the eastern limit of the timbered ridge.

The ice cliff facing the ocean at this point has the general appearance of the front of Muir Glacier, but its submerged profile is different. Instead of deep water it overlooks a shoal, from which boulders project here and there and on which we saw small bergs stranded.[1] Very little floating ice was visible, and no large bergs. The cliff is evidently sapped at base by the wash of the waves, and the process which perpetuates it is closely similar to the process which maintains rock cliffs along other portions of the coast.

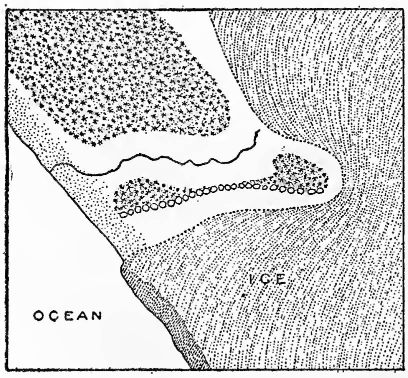


FIG. 21. SKETCH MAP OF MARGIN OF LA PEROUSE GLACIER.

The row of circles marks the position of a fresh-formed moraine ridge, with overturned trees. Forest is indicated by stars, sand beach by dots. Approximate scale; 1 inch=2,000 feet.

The glacier, which farther west presses against the timbered ridge, flows past its end to the sea, and thus the extremity of the ridge occupies a reentrant angle in the margin of the glacier. Close to the angle a stream of water, escaping from the glacier, has crossed the ridge, eroding a deep gash, in whose walls the structure of the ridge is revealed. The walls are not clothed by vegetation, but are somewhat cumbered by the trunks of forest trees fresh-fallen from the crests on either side. The stream has been very active within the last decade or two, and it seems probable that all its work of erosion was

[1] If our visit was at high tide, this shoal may have been bare at low tide.

performed within that period. The section it exposes (fig. 22) includes horizontal beds of blue clay, flanked on the seaward side by highly inclined beds of similar clay alternating with layers of sand. Both these are truncated above, and overlain unconformably by a series of horizontally bedded gravels, in which are incorporated large angular boulders and trunks of trees. This gravel is succeeded on the landward side by — and prob-

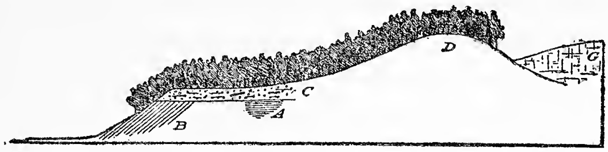


FIG. 22. SECTION OF TIMBERED RIDGE NEAR LA PEROUSE GLACIER.

A, laminated clay. *B*, bedded clay and sand. *C*, bedded gravel, with angular boulders and trunks of trees. *D*, bouldery till, with tree trunks. *G*, glacier.

FIG. 23. BARREN ZONE AT MARGIN OF LA PEROUSE GLACIER (LOOKING SOUTH).

The glacier is at the right. Between it and the forest is a tract occupied by fresh drift, with sticks and logs. Photographed in June, 1899.

ably passes into — a bouldery till, which also contains trunks of trees. The clays and sands evidently represent an epoch when the coast was more deeply submerged than

now, but our meager facts include nothing to indicate either the date of their deposition or the date and manner of their deformation. The overlying gravel and till are clearly of glacial origin, and the gravel was laid down at or near sea-level. As it is now about 150 feet above the sea, it is evident that there has been a change here in the relation of land and ocean. The buried tree trunks tell of an advance of the glacier over a tract that had existed as dry land.

FIG. 24. PUSH-MORAINE NEAR LA PEROUSE GLACIER.

The glacier is out of sight at the left (compare fig. 23). The moraine, here 10 feet high, is crowded against forest trees, and includes crushed trees. Photographed in June, 1899.

The remnant of timber standing east of the stream valley was separated from the glacier at the time of our visit, by a belt of barren ground from 100 to 200 yards wide (fig. 23). This ground was occupied by bouldery till containing bruised and macerated branches and trunk fragments, and the margin of the timber showed unmistakable evidence of recent attack by the ice (fig. 24). The till had been

pushed up into the forest, forming a heap several yards in height, and stones and earth were mingled with trunks of trees and other vegetal débris. It was evident that the forest had recently extended somewhat down the slope toward the present position of the ice, and that a temporary enlargement of the ice field had crowded it back. This had occurred so recently that a younger growth of trees

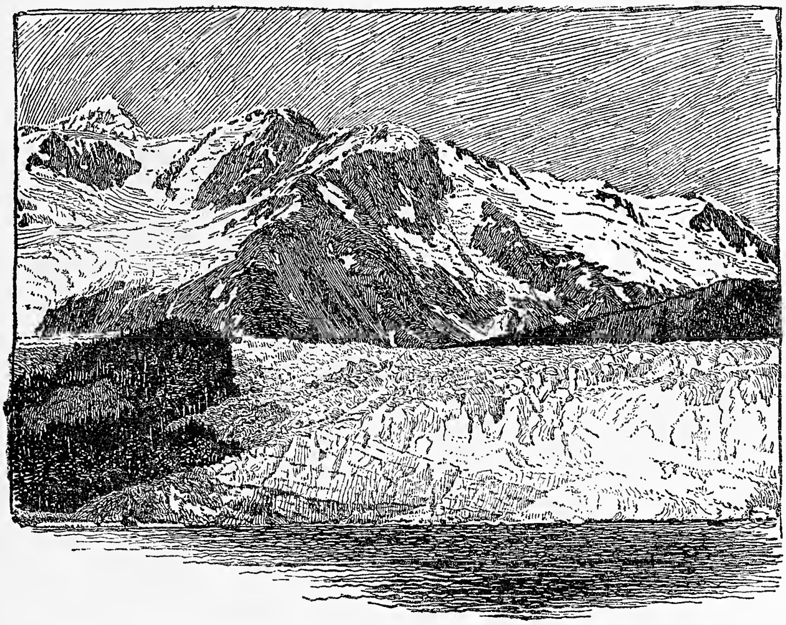


FIG. 25. LA PEROUSE GLACIER—CONTACT WITH FOREST IN 1895.

had not yet started on the morainic ridge. Some of the overthrown trunks still retained their bark, though it had fallen away from most. The wood of the trunks was still sound, but some branches an inch and more in diameter had become brittle, and leaves and smaller twigs had fallen off. With the local woodman's knowledge of the rate of decay in an Alaska forest it would be possible to estimate closely the date of the advance. To my inexpert judgment it appeared probable that it occurred within the last decade of the century.

Since writing the last paragraph I have received from the U. S. Fish Commission a photograph made from the steamer 'Albatross' in September, 1895, and have reproduced it in figure 25. This shows that the ice at that time was in actual contact with the forest.

In the standing timber, which comprises both spruce and hemlock, and also among the overturned trees, are trunks four feet in diameter, and during the whole life of these trees — a matter of centuries — this particular spot has been undisturbed by the ice. It is thus shown that glaciation has here attained within a few years a maximum not previously reached for centuries.

The locality of our visit records at least two glacial maxima. As the older till contains tree trunks, it marks an advance of the ice after an epoch of inferior development. The mature forest standing on this till records another long epoch of lessened glaciation, and the recent advance a second maximum. It is possible that the epoch between the two maxima was of only a few centuries, but evidence to be mentioned in another connection indicates that it was much longer.

On our return voyage in July we passed this part of the coast at a distance of several miles, and I was able to note that the eastern margin of the piedmont division of La Perouse Glacier lay parallel to a forest margin, with an intervening belt of different color, presumably morainic, about 200 yards wide. Similar belts were also seen about the flanks of the next piedmont mass toward the east. These facts indicate that the recent advance recorded at one point on the front of La Perouse Glacier was an advance of the whole glacier, and render it probable that the change was not confined to a single glacier.

The evidence from the crushing of the forest does not tell us whether during the long period before the last advance the ice had approximately its present extent or ex-

perienced an important minimum, but the latter history is rendered probable by comparison with facts recently developed about other glaciers of the same mountain face. Lituya Bay, fourteen miles northwest of La Perouse Glacier, was explored in 1786 by La Perouse, who described and mapped the principal glaciers descending to it. Klotz has made a comparison of La Perouse's account with the condition found by himself in 1894 (fig. 74), and shown that there has been a marked advance of the ice in both arms of the bay, the western glacier encroaching three miles on the water of the bay and the eastern two and one-half miles.[1] The foot of Brady Glacier, twenty-five miles east of the La Perouse, was visited by Vancouver in 1794, and from a discussion of his description Klotz concludes that the ice front was then at least five miles less advanced than in 1894. Muir in 1880 found the margin of the Brady against a mature forest whose territory it was invading. As the La Perouse lies between glaciers of the same range which have experienced a great advance, and as it has recently crowded against a forest, the probability is that its history resembles that of its neighbors and includes a great forward movement during the last century.

YAKUTAT BAY

In the neighborhood of Yakutat Bay a foreland fifteen to twenty-five miles broad separates the mountains from the open ocean. The bay lies partly in the foreland and partly among the mountains. The outer part, to which the name Yakutat is more specifically applied, is nearly twenty miles broad, but narrows toward the mountains. The inner part penetrates the mountain district for ten miles in a north-northeast direction, with an average width

[1] Notes on Glaciers of southeastern Alaska and adjoining territory. Geog. Jour., vol. XIV, pp. 523-534, 1899.

of three miles, and then turns to the right at a sharp angle, and, assuming the character of a narrow fiord, runs back thirty miles toward the south-southeast (fig. 26). It then passes from the mountains to the foreland, and ends in an oval expansion three miles wide. The shorter and broader reach within the mountains is called Disenchantment Bay; the long, narrow arm, Russell Fiord. Russell Fiord has two eastward branches. The northern is at the present time about eight miles long, ending at Nunatak Glacier, and it is convenient to call it Nunatak Fiord. The southern, about one mile in length, leads toward Hidden Glacier.

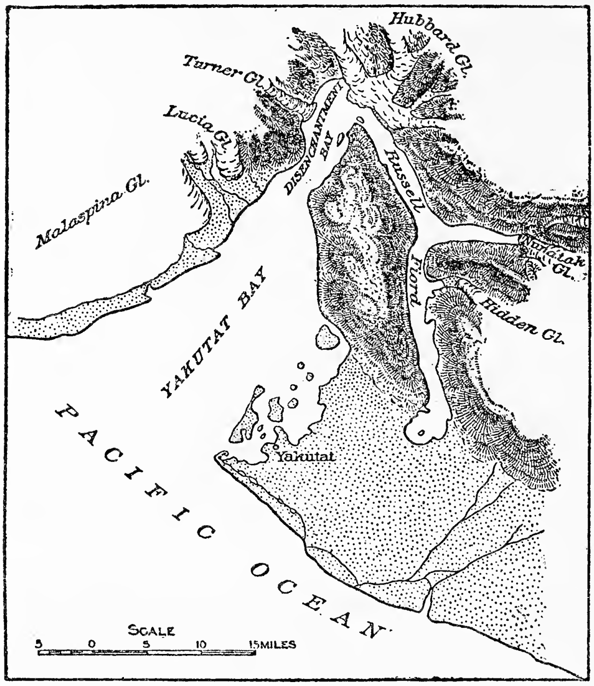


FIG. 26. MAP OF YAKUTAT BAY AND ITS DEPENDENCIES.

Based on map of the Canadian Boundary Commission, with local details by I. C. Russell and Henry Gannett.

The foreland southeast of the bay is in general low, but includes hills and ridges of morainic aspect. So far as known, it is wholly constituted of till and gravel, brought by glaciers and associated streams of water when the ice fields of the region were more extensive. Northwest of the bay the foreland is occupied (or constituted) chiefly by a great piedmont glacier, the Malaspina, the ice being

separated from the water of the bay by a belt of detrital lowland. The mountain system is lofty, and among its summits are great tracts of névé. From these a series of alpine glaciers stream down to feed the Malaspina, and others reach or approach the land-locked arms of Yakutat Bay. Turner Glacier, entering Disenchantment Bay from the northwest, flares at the end after the manner of the Davidson, but has not yet surrounded itself by a moraine barrier, and ends in a berg-producing cliff. The Hubbard, coming in two principal streams from the north and with minor affluents from the east, reaches the sea at the junction of Disenchantment Bay with Russell Fiord and occupies the coast for more than five miles. Nunatak Glacier flows northwestward to the end of Nunatak Fiord, where it maintains a discharging cliff nearly a mile broad. Hidden Glacier, with branches from the east and south, follows a trough parallel to Nunatak Fiord, but fails to reach tide-water, being separated from it by a gravel plain two miles long.

Two islands should be mentioned here, not as important geographic features but as landmarks to which the following pages make occasional reference (see fig. 27 and pl. VIII). Haenke Island, a rounded rock knoll several hundred feet high, lies near the east shore of Disenchantment Bay. Osier Island, lower but containing also a nucleus of rock, stands at the entrance to Russell Fiord.

The inner arms of the bay were explored by Russell in 1890 and 1891, and he prepared a sketch map showing the general relations of fiords and glaciers. The shores were afterward surveyed by the Canadian Boundary Commission (1895), and during our visit Gannett made local maps of the upper part of Disenchantment Bay and the ends of Nunatak and Hidden glaciers.

The prevailing rocks are friable sandstones and partially altered shales, and these are weathered and eroded much

more readily than the rocks about Glacier Bay. For this reason the finer details of ice sculpture are preserved only on surfaces from which the glaciers have somewhat recently retreated. It is probably because of the rapid weathering that vegetation occupies ice-freed surfaces rather quickly, but this remark applies only to herbaceous plants and to willows and alders having the habit of bushes. The spruces, whose dense forests cover the detrital foreland east of the bay and climb the seaward slope of the adjacent mountain, have accomplished little toward the invasion of the most freshly glaciated faces of the same mountain which are turned toward Yakutat Bay and Russell Fiord.

So far as known by direct observation, the recent glacial history is one of waning and retreat. From a careful compilation of early records, made by Russell, it appears that Malaspina in 1792 and Vancouver in 1794, attempting to penetrate Disenchantment Bay in boats, found a glacier front at Haenke Island. This was essentially the face of Hubbard Glacier, to which the Turner was then tributary. Completely filling the head of Disenchantment Bay, it acted as a dam separating Russell Fiord from Yakutat Bay, and the fiord was then occupied by a lake. The discharge of the lake must have been southward over the gravel lowland, and during its existence the wash of its waves produced beaches which are still to be seen as terraces about the southern part of the fiord. Russell estimates their height above tide-water at 150 feet.

From 1792 to 1899 the face of Hubbard Glacier retreated about five miles, but there is no reason to suppose that its position in the days of Malaspina represented a maximum. Haenke Island, which was not wholly covered by the ice at the time of Malaspina's visit, nevertheless preserves glacial striation over the whole of its crest, and in places even polish; and this could hardly be the

case if it had been exposed to the weather for more than one or two centuries. Moreover, there is no change in the vegetation at this point. The alder thickets which begin at the head of Disenchantment Bay, characterize the slopes of the mainland not only to Haenke Island but for miles beyond, and the first spruces noted were not less than five miles to the south of the island. But while the ice seems to have recorded neither a maximum nor a prolonged lingering at the point where it was earliest observed, our present data suggest no other line of critical importance. We can only say that for a period considerably greater than a century the general character of ice change has been diminution.

Since the last paragraph was written, the U. S. Coast and Geodetic Survey has published a new chart of Yakutat Bay, giving soundings from the ocean to Point Latouche, six miles below Haenke Island. These soundings give no indication of a moraine in the vicinity of Point Latouche. Not far from that point there is a depth of 1,000 feet, and thence southward the channel is shown for five miles. Here, at a distance of twelve miles from Haenke Island, is a submerged bar with a depth of about 300 feet, and this is probably the last-formed important moraine in the bay. There appears to be another opposite Knight Island, seventeen miles from Haenke Island, the intervening hollow having an extreme depth of about 600 feet (see fig. 27).

This is the greatest distance to which the channel of the Hubbard, or Disenchantment Bay Glacier can be clearly distinguished. Its course is not central to the bay but nearer the eastern shore, the Disenchantment Bay stream apparently having been crowded over by the expansion of the Malaspina Glacier, which then included the Lucia. Farther to the south and southwest the soundings reveal a series of troughs and ridges whose trend and

curvature suggest that they are connected with earlier positions of the margin of Malaspina Glacier, and these corrugations end against a great shoal which spans the mouth of the bay from cape to cape. This shoal is slightly convex toward the ocean, and its submergence ranges from 50 to 80 feet. It is believed to mark a former extension of the seaward face of Malaspina Glacier.

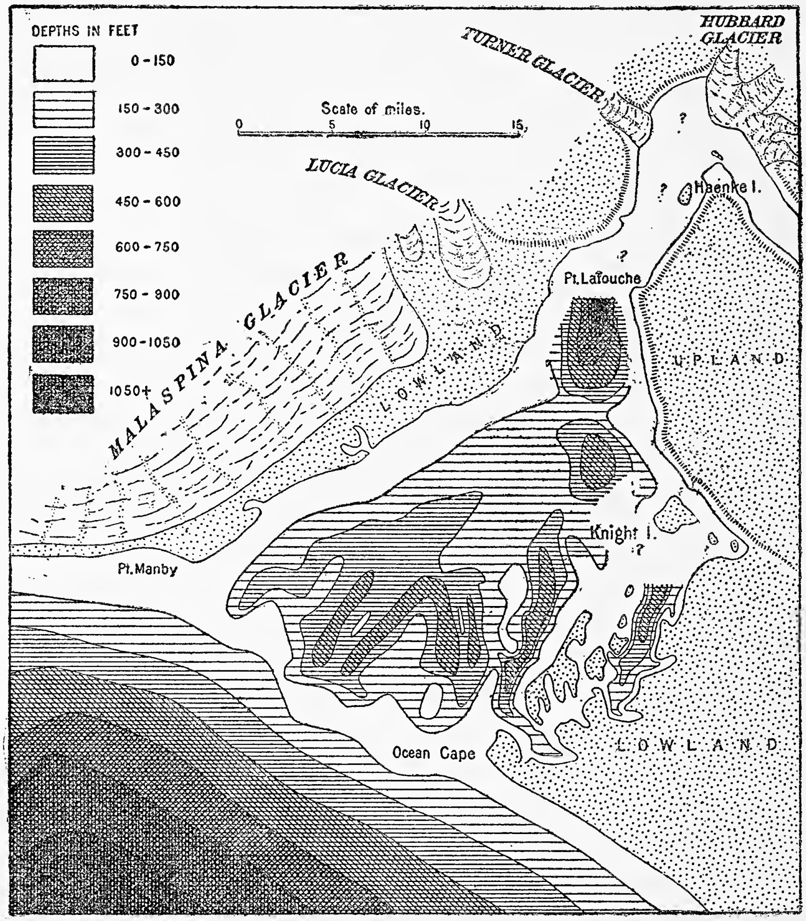


FIG. 27. MAP OF YAKUTAT BAY, SHOWING CONFIGURATION OF BOTTOM.
Adapted from U. S. Coast Survey. Places where no soundings were made are indicated by ??.

All or nearly all of these ridges are probably connected with the Pleistocene history of the region, but the moraine

midway between Point Latouche and Knight Island may correspond to a comparatively recent maximum of the Disenchantment Bay Glacier — that from which it was retreating when observed by La Perouse. A more intelligent judgment can be formed when the system of soundings shall have been carried through Disenchantment Bay.

Turning attention to Russell Fiord, we find pertinent phenomena somewhat more abundant, and it seems possible that their careful study may yield important chapters of the local history. The lower parts of the fiord walls are finely sculptured, showing by magnificent flutings that there has been much longitudinal scouring. At various points, but especially south of Hidden Glacier, there are marginal banks of gravel similar to those about Muir Glacier, characterized by horizontal bedding but showing by their surficial forms that they have been overridden and molded by a glacier. Nearly all parts of the walls of Russell Fiord carry vegetation, of which the alder is a conspicuous element, but the growth is relatively sparse toward the north and dense and luxuriant toward the south. The gravels about the basin at the extreme southern end bear a luxuriant and mature forest of spruce.

Looking back to the time when Russell Fiord was filled by a glacier, it seems evident that the ice stood for a considerable period with a front just outside the mountains. The expansion of the fiord in the edge of the foreland corresponds, I conceive, to the flaring end of Davidson Glacier, and the surrounding plain of gravel is the equivalent of the moraine barrier which the Davidson has built in Lynn Canal. This condition is assumed to date back several centuries, for it is not probable that the forest could occupy the whole surface of the gravels until the ice had retreated. The banks of gravel within the fiord record lingerings of the ice front and subsequent readvances, but whether these oscillations preceded or fol-

lowed the epoch when the entire fiord was filled with ice is a matter of doubt.

Coming to this region while the features of Glacier Bay were fresh in mind, I searched gravel and till, wherever opportunity offered, for vestiges of earlier forests which might have been overridden by the glaciers, but the search was unsuccessful; and so far as my evidence goes, the condition of expanded glaciers observed by Malaspina and Vancouver may not have been preceded in this locality and in recent geologic times by a condition of relatively contracted glaciers such as now obtains. Russell found a buried forest under the foreland gravels at the south end of Russell Fiord,[1] but the demonstrated oscillation need not have been of great extent.

Hidden Glacier. — The valley in which the distal part of Hidden Glacier lies is a characteristic glacial trough with rather uniform cross-section. Its course curves from northwest to a little south of west, and it joins Russell Fiord at right angles. In 1899 for a distance of a mile and a half it was occupied by tide-water with a width of three-quarters of a mile; then came a tract of gravelly alluvium, nearly two miles long and a little narrower than the inlet. The glacier itself had a width of a mile. The ice front sloped gradually down to the alluvial plain, and although the profile was slightly arched, its greatest declivity (measured on a photograph) was only ten degrees. In the lower mile the surface was remarkably smooth and there were no important crevasses. There were lateral moraines, and near the southern of these a single strong medial, but the general face was exceptionally free from drift. Close to the front margin the ice was somewhat discolored, but so nearly white as to suggest that the lower layers, usually dark with englacial drift, were not visible. That they really lay at some distance below the

[1] Thirteenth Ann. Rept. U. S. Geol. Survey, Part II, p. 89, 1893.

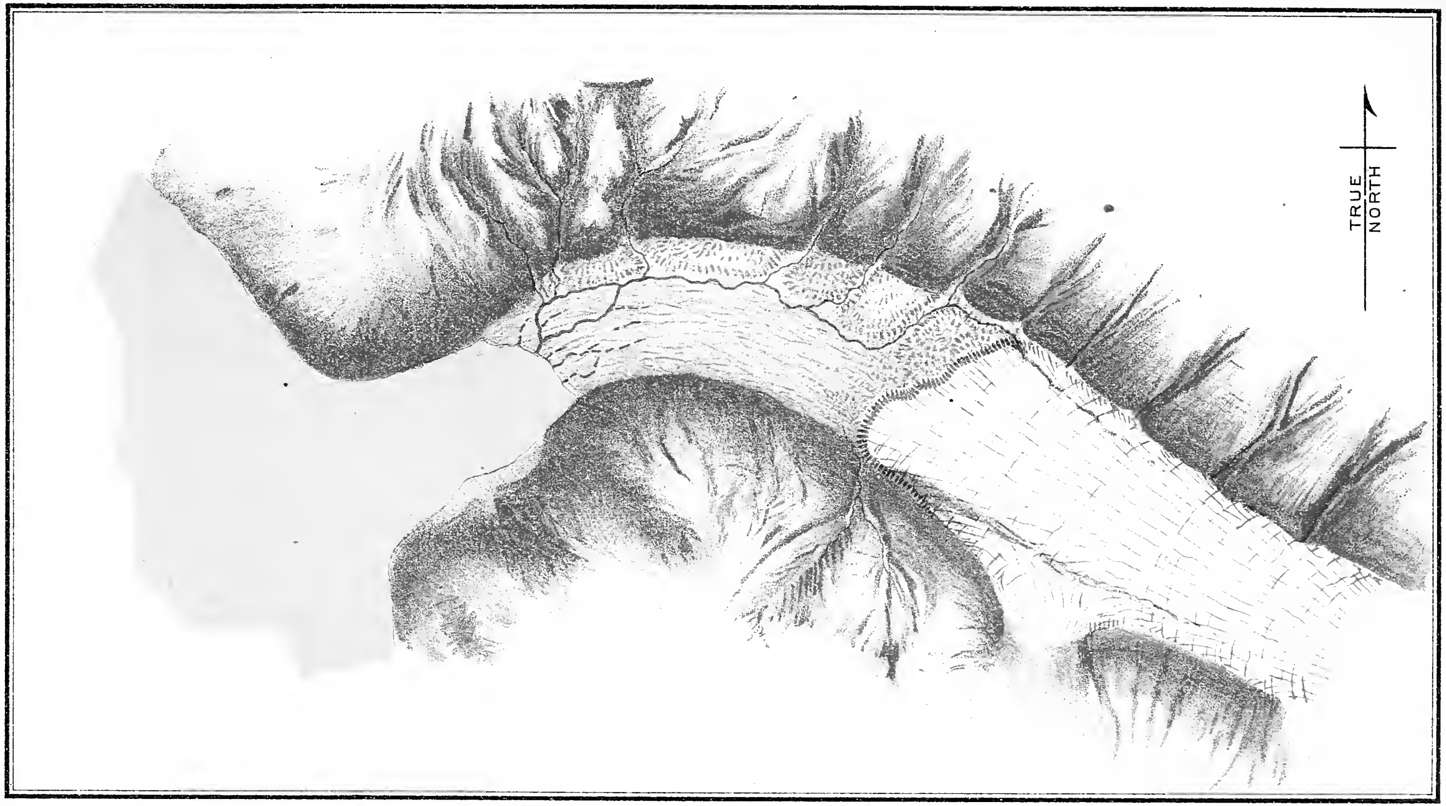
EXPLANATION OF PLATE IV

MAP OF HIDDEN GLACIER

Hidden Glacier reaches the sea at the head of a short arm, branching from Russell Fiord. The whole of the arm is included in the map. For general relations of the locality, see the map of Yakutat Bay, figure 26. For description of the glacier see pages 52–58.

Surveyed by Henry Gannett, June 20, 1899. The chief instrument used was a plane-table, and all stations were on the delta plain between the glacier and the sea. The special purpose of the work was to record the positions, at the time of survey, of the ends of the glacier and delta.

Office drawing by Gilbert Thompson.



MAP OF HIDDEN GLACIER

SCALE

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MILES

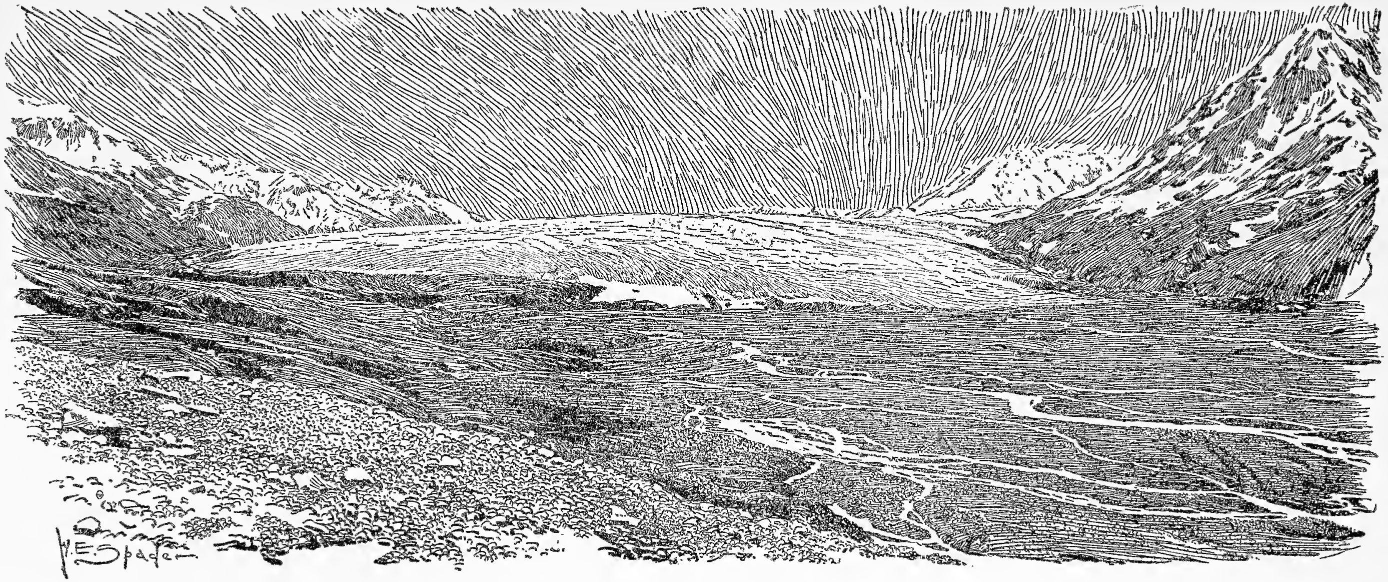


FIG. 28. HIDDEN GLACIER, JUNE 20, 1899.

The glacier approaches Russell Fiord, Yakutat Bay, from the east (see pl. IV and fig. 26). It is here seen from the northwest. Summits of mountains and the extreme distance are concealed by cloud. Width of visible part of glacier, one mile. The lowland at right is a typical illustration of the barren, stream-built waste plains associated with many Alaska glaciers. At the left is rudely stratified gravel, the remnant of an older waste plain which has been over-ridden and eroded by the glacier.

visible glacier snout and were extended along the floor of the valley beneath the gravel plain, seemed to be shown by other phenomena. First, the water of ablation, though flowing out from the surface of the glacier near each side, did not visibly escape from the ice in the central part, but oozed up through the contiguous gravels, gathering in a number of streams, which attained their full size about a quarter of a mile from the ice front. Second, the gravel plain in the vicinity of the ice front was dotted by numerous pits, the larger of which contained lakelets. The sides of these pits were steep and exhibited the stratification of the gravel in section, the pits having evidently been formed after the gravel was deposited; and there can be no doubt that they originated from the melting of buried ice and the consequent sapping of the gravel bed. The ice whose melting was thus demonstrated may have been part of a continuous sheet or may have constituted a series of isolated masses, but in either case each local mass must have reached its position as part of the glacier. The history seems to be, that the waning glacier was so reduced by the wasting of its surface near its end that the débris of its moraines, worked over by glacial streams, overspread the ice and buried a wide belt. At the time of my visit this was gradually and irregularly melting, under the influence of underground waters, and by its melting was sapping the gravel plain.

This process is of interest to students of Pleistocene glaciology, because it is evident that with a slight change of conditions it might lead to the formation of familiar features of the 'modified drift.' If the locality lay somewhat higher above tide, and if the glacier were so situated that, with the progress of its melting, the water of ablation would be drawn off in some other direction, the gravel plain would be left intact except for such changes as resulted from the melting of the ice beneath it. Where

EXPLANATION OF PLATE V

KETTLE-HOLES NEAR HIDDEN GLACIER

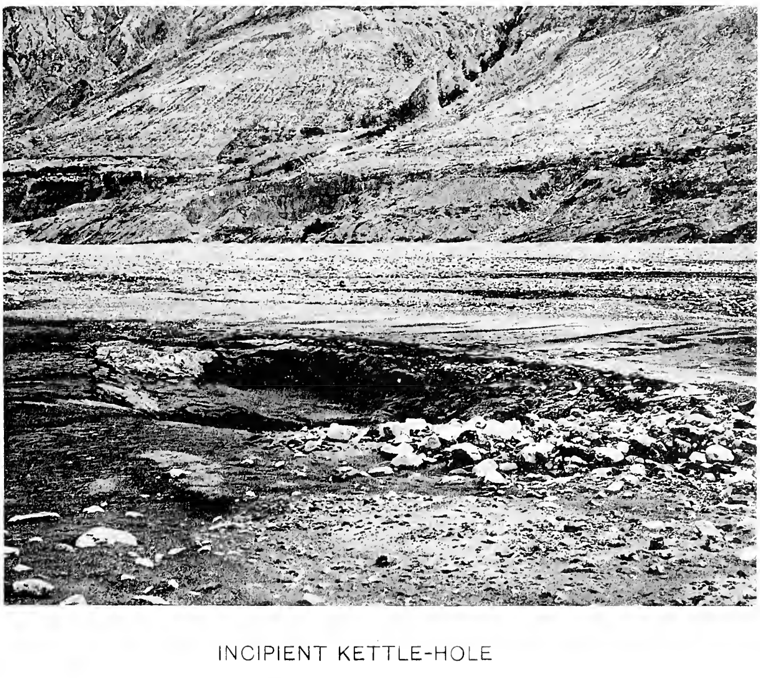
Kettle-holes are ascribed to the melting out of ice masses that had been buried by the rapid accumulation of gravel or sand. In the cases pictured the burying material was gravel washed from Hidden Glacier, and the ice masses were originally part of the glacier.

The *Upper Figure* shows a fresh-formed example, the steep walls exhibiting the gravel deposit in section. It shows also the gentle terminal slope of the glacier, the smooth sculpture of its valley wall, and the mouth of a hanging valley. See pages 55 and 118.

The *Lower Figure* shows a less advanced stage of the same phenomenon. After settling had commenced, the spot received a deposit of mud, and this mud was cracked as the settling proceeded.

Photographed by G. K. Gilbert, June, 1899. Negatives NOS. 371 and 372, United States Geological Survey.

KETTLE-HOLE



INCIPIENT KETTLE-HOLE

HELIOTYPE CO., BOSTON.

that ice was approximately or wholly continuous, its melting, being temporarily concentrated here and there by underground currents, would let the gravels down unequally and leave them, in the end, in a system of irregular heaps identical with kames. Where the surviving ice comprised only isolated or scattered masses, the waste of these would let down the gravels immediately above them, producing steep-sided, crater-like kettle-holes, and creating the familiar phenomenon of a pitted plain.

The upper figure in plate v reproduces a photograph of one of these fresh-formed kettle-holes, lying near the visible portion of the glacier. Its dimensions were 220 feet by 70 feet, with a depth, to the water surface, of eight feet. Its wall was divided at one point by an outlet channel leading to a neighboring glacial creek. An incipient kettle-hole seen about a mile below the glacier is represented in the lower figure. This had been overflowed by water from one of the glacial creeks, so as to receive a layer of mud, but the water had retired before it was wholly silted up. It is evident that the meandering of streams over the gravel plain would eventually obliterate all of the kettle-holes, so that their preservation must depend upon some permanent diversion of the streams.

The stream escaping from the north edge of the ice front was traced backward to an ice cave among the hillocks constituting the lateral moraine. It was evident from an examination of the local topography of the ice surface that the débris had great influence on the rate and method of wasting, and reciprocally, that the wasting modified the distribution of the débris. Where the débris was more than a few inches thick it retarded melting, producing an ice hill; but from these hills the stones slid down to the neighboring hollows, producing accumulations which in turn retarded melting and caused a new distribution of hills. Some of the hills were elongate,

and may have marked the position of original moraine belts, and one of these happened to be cut across by a glacial stream, so as to be exhibited in section. In the photograph reproduced in plate VI the ice, which is here rather dark from suffused dirt, is seen to constitute the mass of the morainic ridge, being preserved from melting by a relatively thin layer of fine drift.

Russell, who saw and named the glacier in 1891, did not visit it, and merely records that it was non-tidal. His map makes no claim to precision and can not be used in a comparative way to determine the history of change. Gannett's map, pl. IV, and the various photographs here reproduced, make a record which will be available for future comparison, but inference as to past changes can only be based on circumstantial evidence. That the recent history of the glacier has been one of recession can hardly be doubted. Not only do the kettle-holes testify to the stagnation and burial of what was formerly its snout, but I found remnant ice masses above the gravel plain on both sides of the valley. These were protected from rapid waste by gravels that were originally parts of lateral moraines, but as water was constantly flowing from them their survival could not be indefinitely prolonged, and their origin can not have been remote. They were not seen more than a half mile from the ice front, but they lay considerably above the neighboring gravel plain, the extreme height at the north being estimated at 300 feet, and at the south somewhat greater. When the back of the glacier reached to these heights its front probably extended a mile farther down the valley.

The walls of the valley are not clothed with vegetation, but a scattering growth of annual plants and a few dwarf willows have found foot-hold. The gravel plain through which the glacial streams meander, though seemingly affording conditions of soil and moisture congenial to

EXPLANATION OF PLATE VI

Upper Figure. — Profile of Hidden Glacier

Shows the relation of the glacier snout in June, 1899, to topographic details of the south wall of the valley. In the foreground are bedded gravels that have been overridden, eroded, and grooved by the enlarged glacier, and are now being trenched by running water.

The amphitheater high in the mountain shows familiar forms of aqueous sculpture but is not continued downward in a gorge of commensurate size. The gorge probably once existed, but the containing spurs were removed by ice erosion at a time when the glacier was much larger than now.

See page 52, and compare figure 28.

Photographed by G. K. Gilbert, June 20, 1899. Negative no. 368, United States Geological Survey.

Lower Figure. — Section of Moraine

Shows the structure of one of the ridges of the northern lateral moraine of Hidden Glacier. See page 56.

Photographed by G. K. Gilbert. Negative no. 370, United States Geological Survey.

PROFILE OF HIDDEN GLACIER

SECTION OF MORAINE

HELIOTYPE CO., BOSTON.

arctic willows, was absolutely barren (fig. 29), and a similar barrenness was observed on other fresh-formed streams of glacial waste. The perpetual stream of cold air flowing down from the ice above may be in part responsible for

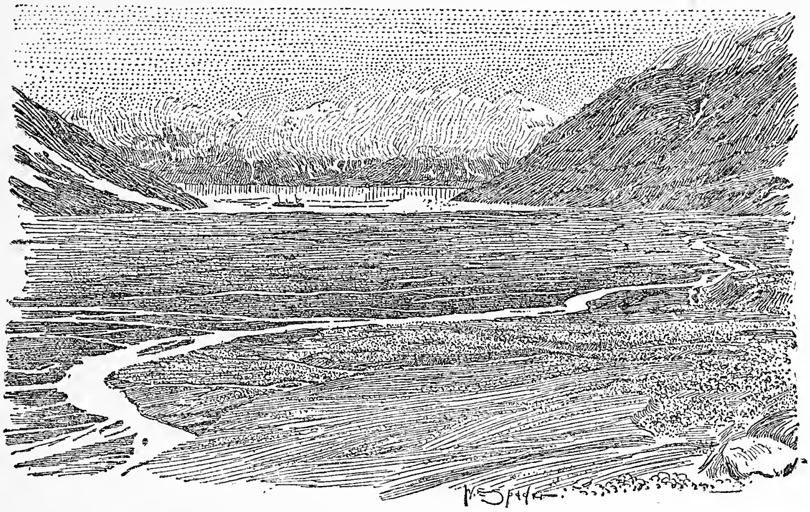


FIG. 29. WASTE PLAIN OF HIDDEN GLACIER IN JUNE, 1899.

The rock fragments washed from the glacier are built into a delta plain, to which addition is being made. In the foreground is an alluvial fan encroaching on the plain; in the distance, Russell Fiord.

this, but I conceive the chief cause to be rapidity of deposition. The high grade of the plain, in comparison with the breadth of its channels and the moderate coarseness of its gravel, gave the impression that it was being built up with great rapidity.

As in Russell Fiord and its other appendages, the valley walls exhibit the flowing contours of glacial sculpture in magnificent development. There are many places where the smooth curves of the mountain side, carved out in harmony with the flow-lines of the ice, suggest the sweeping contours of a gigantic ship, rather than the billowy backs of a flock of sheep described by the word moutonnée. A system of flutings can often be traced in simple curvature for a half mile, and no one familiar with the

topography resulting from stream erosion can fail to be impressed with the profound modification here wrought by the ice. (See fig. 102.)

As the extent of the glaciers has varied, masses of gravel and other drift have been lodged here and there on the valley walls and afterward overridden, and where the subsequent action has not sufficed for their removal they have been carved into forms harmonious and continuous with the contiguous rock forms. Here and there, where the rills of the valley wall have trenched these deposits so as to expose them in section, one may see horizontal bedding in a mass of gravel whose external surface exhibits only the smooth curves of flowing ice. One of the larger of these gravel masses lay close to Hidden Glacier, against the lower slope of the north wall of the valley (pl. v). Upon its sculptured back were scattered boulders left by the ice which had recently overridden it, and among them were a few great blocks of white granite, brought from some distant source. Descending toward the glacier, the surface of this gravel mass ran under one of the remnants of unmelted ice to which reference has already been made.

Nunatak Glacier. — Nunatak Fiord, like the fiord of Hidden Glacier, has been boldly sculptured by ice. Its lofty south wall descends steeply to the water and is comparatively simple in contour. The north wall is in general lower, is flanked by heavy masses of gravel and other drift, and is interrupted by two branching troughs leading over saddles of moderate height to the northern part of Russell Fiord. These troughs seem to have been largely shaped by the ice, which flowed through them to the northwest. One is now bare, but the other contains an ice mass with the habit of the dying glaciers of Glacier Bay. The mass receives a small tributary glacier near its summit, but the end seen from Nunatak Fiord in 1899

EXPLANATION OF PLATE VII

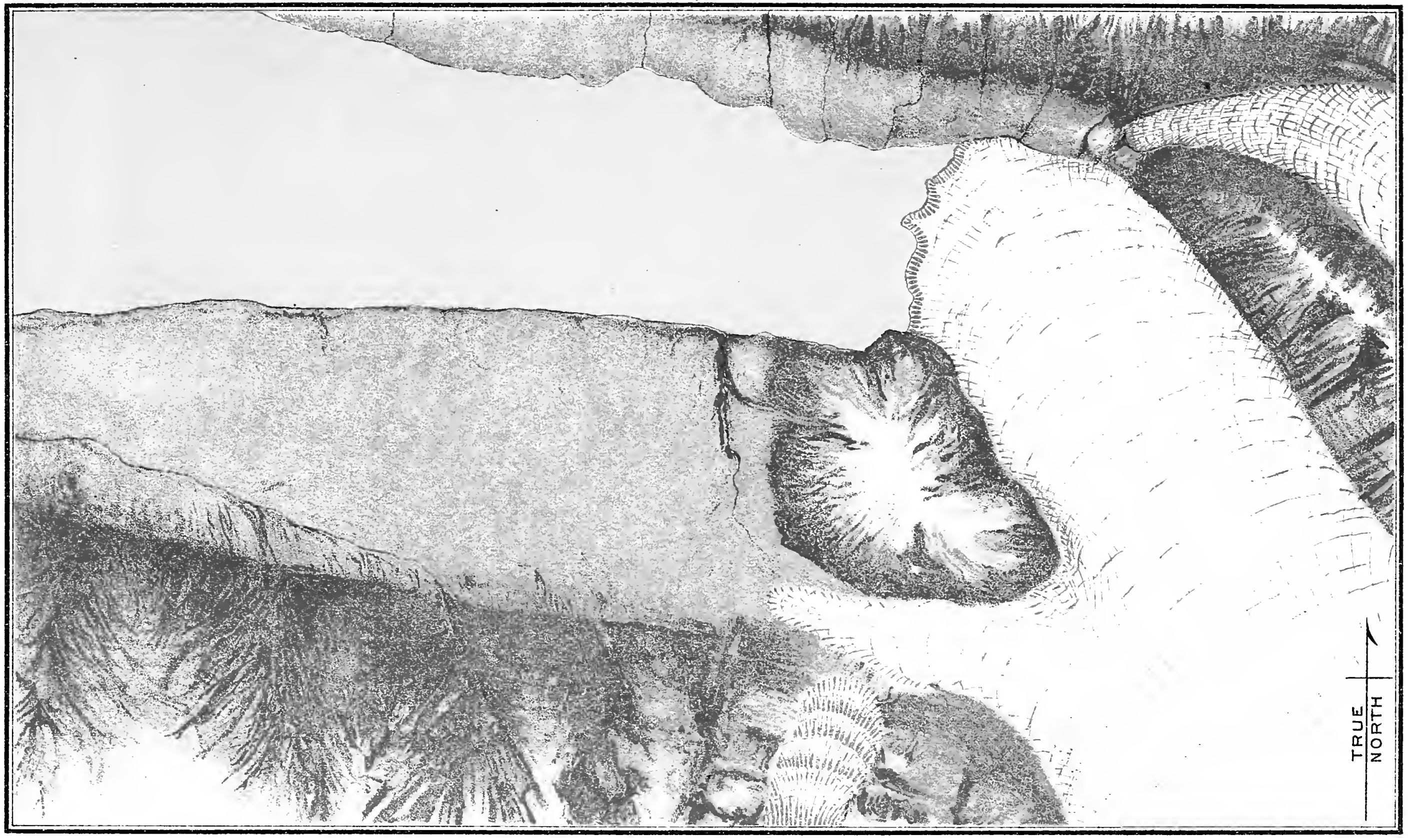
MAP OF NUNATAK GLACIER

Nunatak Glacier reaches the sea at the head of Nunatak Fiord, an arm joining Russell Fiord at right angles. See map of Yakutat Bay, figure 26.

This map is based on a plane-table sketch by Henry Gannett, made from stations on the north shore of the fiord, June 20, 1899. Special pains were taken to make record of the ice cliff terminating the north arm of the Nunatak Glacier. Its south arm, and the minor glaciers, were added from photographic data and eye observations, without the aid of instruments.

Drawn by Gilbert Thompson.

See pages 58–63.



MAP OF NUNATAK GLACIER

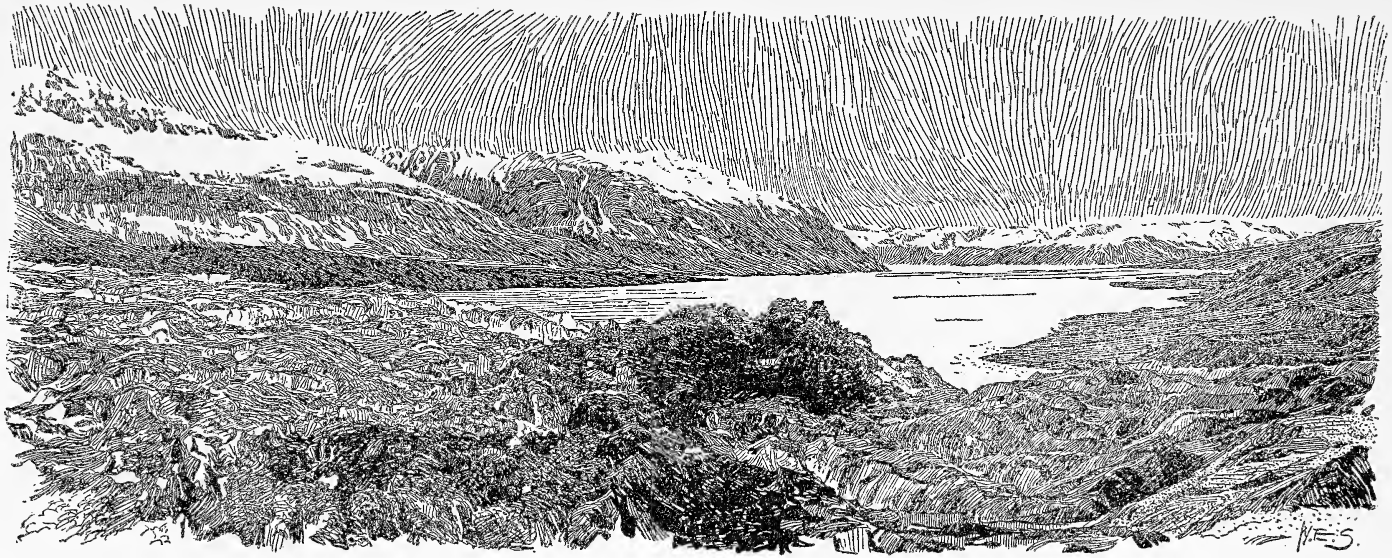


FIG. 30. WESTWARD FROM NUNATAK GLACIER.

The observer stands on a morainic band of Nunatak Glacier, near the cliff which terminates it (fig. 34), and looks down Nunatak Fiord to Russell Fiord. The distant mountains, partly concealed by cloud, are the west wall of Russell Fiord. The wall of Nunatak Fiord owes its smooth contours to ice erosion, the extent of which is suggested by the mouth of a hanging valley.

was probably stationary and wasting. It was heavily coated with drift, which lay in irregular hummocks. The opposite end was not identified, but may be one of the branches of the stagnant portion of Hubbard Glacier, to be described on another page.

Close to the end of Nunatak Glacier were two lateral glaciers which may recently have been its tributaries.

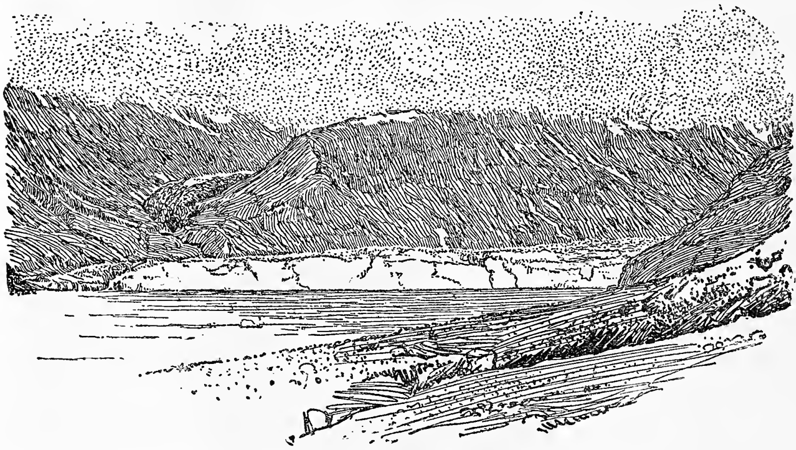


FIG. 31. TIDAL FRONT OF NUNATAK GLACIER.

Beyond it, a hanging valley, with a small glacier. The heights are hidden by cloud. Photographed from the southwest, June 21, 1899.

That at the north (fig. 31) occupied a trough trending nearly east and west and intersecting the Nunatak at an acute angle. It terminated several hundred feet above the Nunatak, its lower part being buried under a heavy moraine. That at the south (fig. 32) probably occupied a yet higher valley nearly at right angles to the Nunatak trough, but clouds cut off the view of its upper portion. It was seen only as a series of ice cascades, pouring from ledge to ledge for a thousand feet down the steep wall of the trough.

The main division of Nunatak Glacier was tidal, discharging bergs freely from a cliff nearly a mile long and about 200 feet high. At the south the cliff ended against

a bold rock shore, but at the north it terminated among gravels, and a narrow remnant of ice, half buried, extended several hundred yards west of the main mass. Near and east of the position of the glacier front is a high rock terrace against the south wall of the valley, and this culminates at the east in a bold knob, thoroughly smoothed and rounded by recent glaciation. In the hollow separating this knob from the south wall lay a mass of ice of uncertain relations (fig. 33). It was seen only from the west, and was supposed to be a tongue or distributary arm of Nunatak Glacier. The fact that it lay several hundred feet higher than

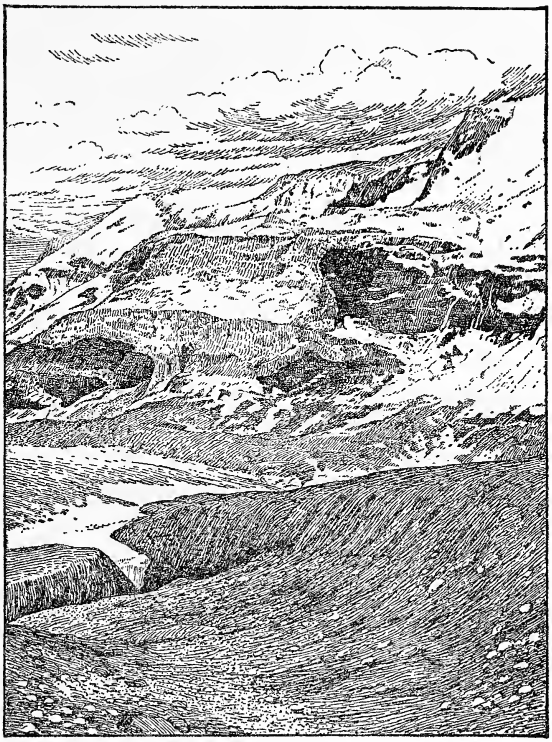


FIG. 32. CASCADING GLACIER IN NUNATAK FIORD.

The visible portion of the glacier has no valley, but descends wall of valley of Nunatak Glacier. Photographed June 21, 1899.

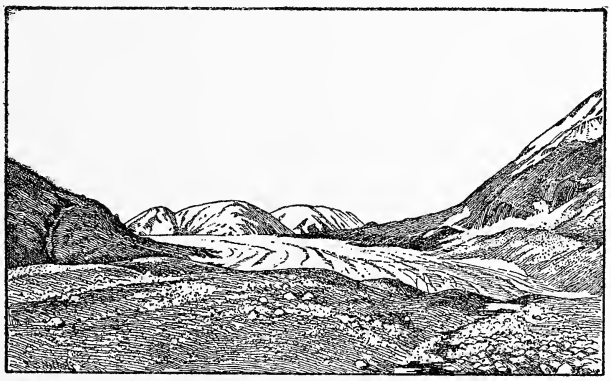


FIG. 33. SOUTH TONGUE OF NUNATAK GLACIER IN 1899.

the tidal arm has raised doubts as to the correctness of the first impression, and I now suspect that it was only the remnant of a former arm of the glacier, stranded as a motionless and slowly wasting summit mass. On the map of the Canadian Boundary Commission (1895) it is represented as a distributary of the glacier.

At the time of Russell's visit in 1891 the glacier flowed on both sides of the high rock knob (fig. 34) and was reunited beyond it, so as to convert the knob into a nunatak; and it was this conspicuous nunatak near the end of the glacier which suggested its name. The retreat of the ice front in the intervening eight years can not have amounted to less than a mile and may have been twice as great. It was nearly all accomplished in the first half of the period, for the photographs made by the Boundary Commission in 1895[1] show a complete separation of the two arms and a close approximation to the condition of 1899. The tidal arm was perhaps a third of a mile more advanced in 1895, but the non-tidal was not appreciably longer. It is possible, however, that the latter extended for some distance in a stagnant condition beneath a mantle of drift, for at the time of our visit there appeared to be remnants of ice in a moraine belt stretching for a mile beyond its extremity.

FIG. 34. TIDAL FRONT OF NUNATAK GLACIER.

Photographed from the north, by D. G. Inverarity, June 21, 1899. The camera stood on the glacier.

The accompanying map (pl. VII) is based on the survey by Gannett in 1899, supplemented by photographs. It is accurate as to the ice front and contiguous land, but

[1] Nos. 20 and 45, on pages 7 and 17 of vol. 17 of the official album.

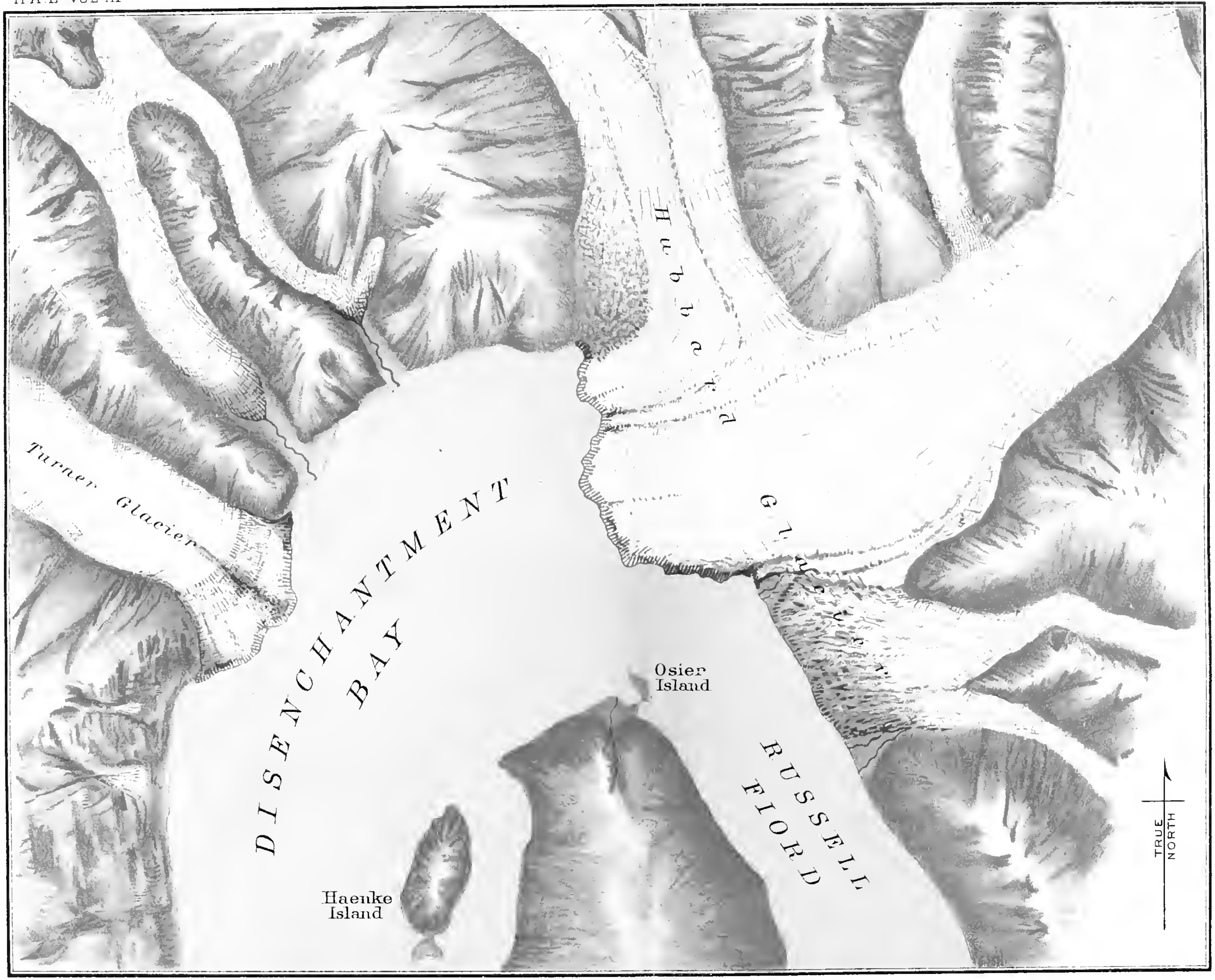
EXPLANATION OF PLATE VIII

Map of Hubbard and Turner Glaciers

The Hubbard and Turner glaciers reach the sea at the head of Disenchantment Bay, an inner member of Yakutat Bay. See map of Yakutat Bay, figure 26, and description on pages 63–69.

Surveyed by Henry Gannett, June 21 and 22, 1899, from stations on both sides of Russell Fiord and on Osier and Haenke islands. Details in the northeast corner were added from sheet No. 23 of the Canadian International Boundary Commission's map.

Drawn by Gilbert Thompson.



MAP OF HUBBARD AND TURNER GLACIERS

SCALE 0 1 2 3 4 MILES

only approximate in its reproduction of the other portions of Nunatak Glacier and the neighboring ice bodies.

Hubbard Glacier.— The Hubbard Glacier, discovered by Russell in 1890 and named by him in honor of Gardiner G. Hubbard, president of the National Geographic Society, is the most important ice body of Yakutat Bay. Its width where it reached the bay was, in 1899, five and one-half miles, its whole frontage, counting the sinuosities of outline, being about six miles. Of this frontage the southeastern third was motionless, and fringed for the most part by a belt of morainic débris. The remainder, pushing itself forward into the head of Disenchantment Bay, maintained an imposing ice cliff nearly 300 feet high. The active portion of the glacier had two main branches, the larger coming from the east or northeast, the smaller coming from the north, and the two uniting only three miles back from the water. Looking up the valley, we could see a number of minor tributaries descending from the bordering heights, but the principal sources were concealed from view, and the low grade of the main trunks suggested that their beginnings were far away. The surfaces of both branches were rugged, being divided by a labyrinth of crevasses into a wilderness of pinnacles. Morainic bands marked out the lines of flow, and a broad belt of ice near each margin of the active portion was black with included débris. The more southerly of these belts was continued to the water front, causing a black ice cliff nearly a mile in extent (fig. 35). The corresponding belt at the north appeared to have become nearly stationary, as though resting on a rock shoal, and the flow-lines of the northern arm were curved about it.

The southeastern third of the glacier was moraine covered, not only at the water edge but for nearly or quite two miles inland. The material was coarse and angular, and was divided into zones or belts distinguished at a

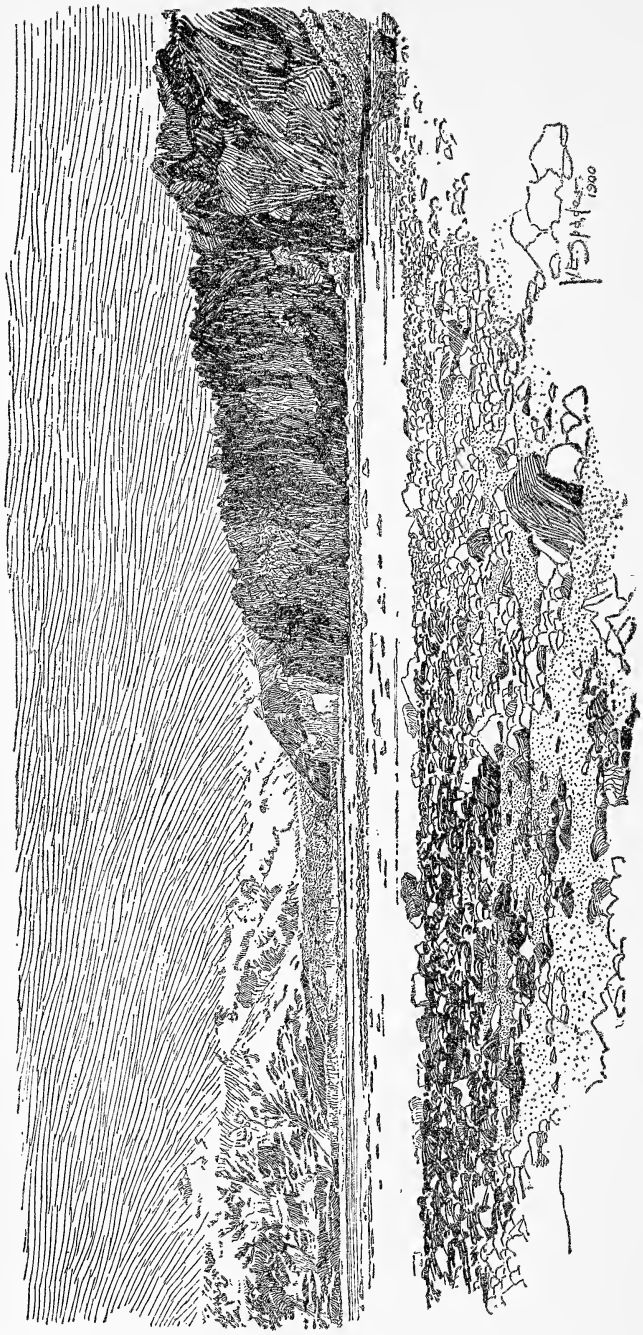


FIG. 35. HUBBARD GLACIER, JUNE 21, 1899.

The ice cliff of the glacier towers 300 feet above Disenchantment Bay. Nearby it is black with included rock waste, but beyond clean and white. In the distance Turner Glacier. Compare plates VIII and IX.

EXPLANATION OF PLATE IX

Upper Figure. — Panorama of Hubbard Glacier

The glacier reaches Disenchantment Bay, an inner part of Yakutat Bay, from the northeast. See plate VIII.

The point of view is on the fiord wall, back of Osier Island, 1,000 feet above the water. Some of the higher peaks are obscured by cloud. The main streams of ice come from the north and northeast, and push forward to Disenchantment Bay (at left), into which bergs fall. Feebler streams from the east are unable to move the piedmont body against which they end, and the latter, accumulated at an earlier epoch, is stagnant and wasting, its surface dark with residuary rock débris.

See pages 63–66.

Drawn by W. E. Spader, from photographs made by G. K. Gilbert, June 22, 1899. Negatives NOS. 312, 313 and 314, United States Geological Survey.

Lower Figure. — Panorama of Columbia Glacier

The glacier reaches Columbia Bay, an arm of Prince William Sound, from the northeast. See plate XI and figure 37.

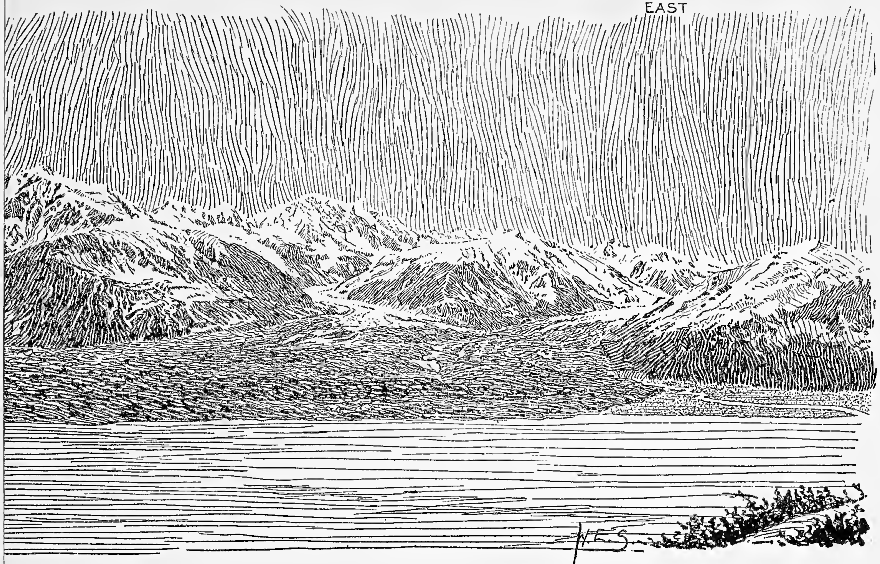
The point of view is a mile east of the glacier and 1,000 feet above tide — approximately at timber-line.

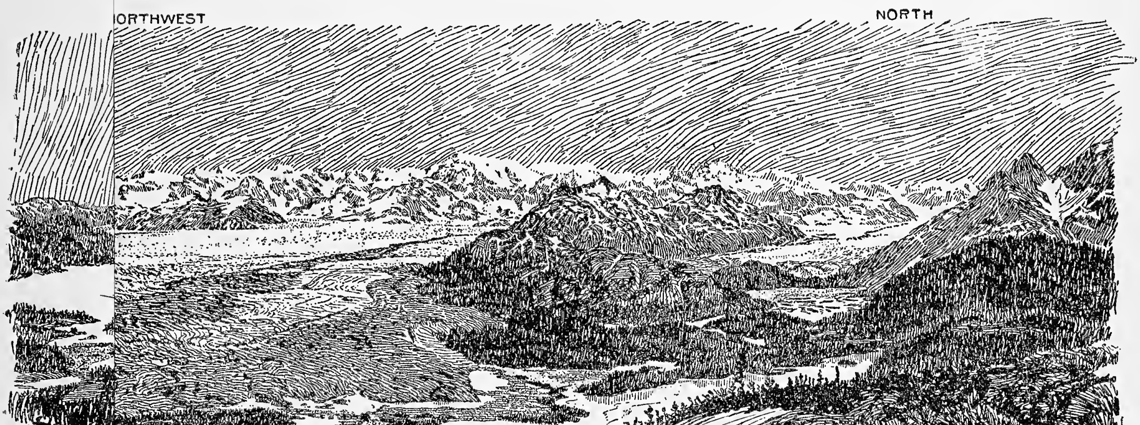
The main sources of the ice river are at the north. A little west of north stands an isolated mountain (3,500 feet) which divides the current. The main stream passes beyond it, but minor lobes embrace it, making it a nunatak. Thence to the bay the broad medial zone of white ice presents a wilderness of pinnacles and crevasses. A marginal zone, moving more slowly, is somewhat less rugged, but black with rock fragments. A tract of bare ground separates this zone from the forest. The bodies of water at the northwest and north are glacial lakes; that is, they are contained on one side by the ice. The extreme salient of the ice front touches a group of islands dividing the bay. Where the ice is met by the water of the bay it ends in a vertical wall, from which bergs fall.

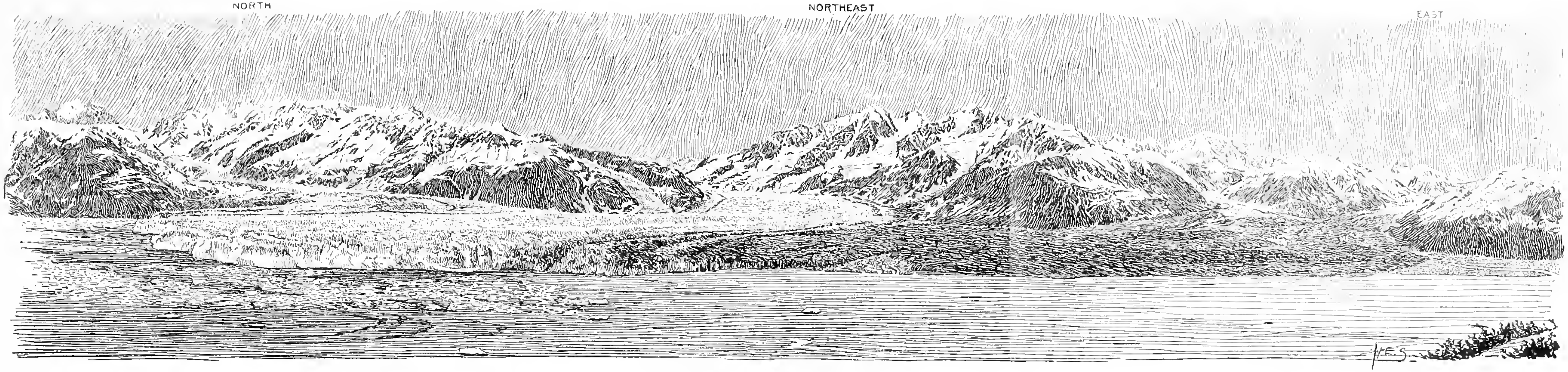
The nunatak, the mountains in middle distance toward the northwest and west, and all mountains seen to the southwest, were submerged by the Pleistocene ice flood.

See pages 71–81.

Drawn by W. E. Spader, from photographs made by G. K. Gilbert, June 26, 1899. Negatives NOS. 340 to 344, United States Geological Survey.


EAST


ORTHWEST
NORTH



PANORAMA OF HUBBARD GLACIER

PANORAMA OF COLUMBIA GLACIER

distance by their contrasted colors—black, yellow, purple, green, blue-black, and orange or rusty. These bands had not the ordinary arrangement of parallel medial moraines, but tended rather to contour the slope, and the search for their origin and meaning would make an interesting and profitable study. Some of them occupied ridges and others hollows, suggesting inequality in their ability to retard the melting of the ice beneath, but the whole surface was rugged in detail, exhibiting a continuous series of hummocks and kettles.

The map given in plate VIII was made by Gannett from a series of stations at the south, the northern shore of Disenchantment Bay being inaccessible by reason of floating ice; and some of the details, especially of the moraines, were added by the aid of a series of photographs made from a high station on the mainland near Osier Island. Russell in 1891 (September 5) stationed his camera on Osier Island; and a comparison of his photographs with mine (June 22, 1899) shows that there was little change in the general character and condition of the ice cliff. My views place it one or two hundred feet farther back than his, and this difference would probably be increased if the proper correction for season could be applied (p. 22), but in any case the estimate of the whole retreat would not exceed a few hundred feet, and would be very small as compared to the retreat of Nunatak Glacier in the same period.

A photograph taken from Haenke Island in 1899 is also comparable with one from the same station by the Canadian Boundary Commission in 1895,[1] each showing the relation of the northern part of the ice front to the features of the contiguous mountain face; and in this case also the recorded change is small.

Another series of photographs were made by the U. S. Fish Commission in 1901, chiefly from Osier and Haenke

[1] No. 13, on page 5 of vol. 17, official album.

Islands; these show a continuance of retreat. At a point where a prominent moraine makes the comparison somewhat definite, the ice cliff appears to have then stood 700 to 1,000 feet farther back than in 1899. The cliff was also shortened at each end by the enlargement of the marginal belts of stagnant ice.

Turner Glacier. — Turner Glacier comes into Disenchantment Bay from the northwest, a few miles below the foot of Hubbard Glacier. As already stated, it was tributary to the Hubbard a century ago, and was rendered independent by the retreat of the latter. Immediately after its isolation its front may have projected somewhat farther into the bay than in later years, but it is not probable that the difference was great. A comparison of Russell's photograph made from Haenke Island in 1891 with my own made eight years later from the same station (pl. x) shows no appreciable change in the position of the front.

The general width of the glacier within the mountain is about one mile, but it begins to flare before fully emerging, and at the water front was nearly two and one-half miles broad in 1899. For a width of about two miles an ice cliff was maintained by the falling of bergs, and the cliff was flanked on either side by a sloping tongue which, from our distant view, seemed black. Russell's picture represents parts of these tongues as white, so that in these marginal portions a progressive change is recorded. There was also a change in the flow-lines, as indicated by moraines near the southwestern margin. A strand of the ice which had previously swung far to the south had in 1899 acquired a more direct course to the bay, reaching the cliff 1,200 feet to the northward. This would seem to indicate that a body of ice near the south end of the water front had in the interval become stagnant and, acting as an obstruction, had deflected the current.

EXPLANATION OF PLATE X

Upper Figure.—Turner Glacier in 1891

Photographed by I. C. Russell, September 5, 1891. Negative no. 556, United States Geological Survey.

Lower Figure.—Turner Glacier in 1899

Photographed by G. K. Gilbert, June 22, 1899. Negative no. 317, United States Geological Survey.

Each of these photographs was made from near the summit of Haenke Island, the stations being practically identical. The changes in the glacier from 1891 to 1899 are discussed on pages 66–67.

The position of the glacier, on the west side of Disenchantment Bay, is shown in plate VIII and figure 26.

TURNER GLACIER IN 1891

TURNER GLACIER IN 1899

HELIOTYPE CO., BOSTON.

Since writing the preceding paragraph I have been able to extend the comparison by examining photographs by the Canadian Boundary Commission and the U. S. Fish Commission. That by the Boundary Commission was taken from Haenke Island[1] in 1895, its record being midway between Russell's and mine. It shows the condition of each feature as intermediate between the phases of 1891 and 1899. That by the Fish Commission was taken from Osier Island in 1901. It shows an extension of the frontal cliff, as compared with the condition in 1899, and probably indicates renewed movement in marginal ice which had become stagnant.

There is an important morainic belt on each margin of the glacier, with outlying ribbons, and a single well-defined medial moraine reaches the water front near its middle.

The visible portion of the glacier within its mountain valley has a moderate grade, but at its débouchure into the main trough of Disenchantment Bay there is a steep descent, the surface falling 500 to 600 feet in a quarter of a mile. The grade then suddenly diminishes to almost nil, and the glacier terminates in a platform of nearly uniform height, with a width ranging in different parts (1899) from 1,800 to 3,500 feet.

The ice cascade at the point of débouchure indicates a drop in the rock bed where the Turner trough joins the greater trough of Disenchantment Bay, and this feature is related to the phenomena of hanging valleys, to which special attention will be given in another chapter. The flatness of the terminal portion of the glacier is a peculiar feature, not so strikingly exhibited to us in any other instance. It is of course possible that the longitudinal profile of the glacier bed is here horizontal, and that the ice is everywhere supported by a floor of rock or drift; but it seems to me more probable that the flatness is due to

[1] No. 12, on page 5 of vol. 17, official album.

flotation. If the glacier rested on a solid support there would be retardation from the friction on its bed, and this resistance would tend, under the laws of glacier motion, to produce a surface gradient.

If it be true that the ice is floated, then the sea water has access to its under surface, and the rate of melting is greater than would obtain if the front only were exposed. Should an increase take place in the supply of ice from the névé, and consequently in the size and speed of the ice stream, the end of the glacier would be thrust farther out on the water of the bay, but this extension would increase the surface exposed to melting, and the loss thus occasioned would soon check the enlargement. The opposite result would follow a diminution in the supply of ice, and the equilibrium between supply and waste would thus be maintained without great modification of the form and extent of the ice front. There would of course be progressive modification from the silting up of the bay. Direct melting of the under surface of the glacier before the mass is broken up into bergs would tend to localize the deposit of drift, so that the accumulation under the ice would be quite rapid, and eventually the drift floor would reach up to the ice and subglacial melting would be checked.

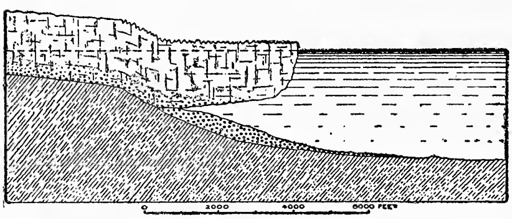


FIG. 36. HYPOTHETIC LONGITUDINAL SECTION OF TURNER GLACIER.

If the glacier floats, its thickness can be estimated from the measurement of the visible portion. In water of such density as Reid observed in Glacier Bay, the ice of glaciers floats with about seven-eighths of its mass submerged; and the thickness of the visible portion of the tabular mass in question would be one-eighth of the total thick-

ness. The central part of the Turner ice cliff in 1899 was 250 feet high, but as the surface of the glacier was greatly dissected by crevasses its average height above water was somewhat less and may be roughly estimated at 220 feet. This would give for the total thickness 1,760 feet, and for the submerged portion 1,540 feet. The theory that the glacier floats, thus implies that the bay has a depth close to the northwest shore of 1,600 feet, and the central depth should be considerably greater. The theory could therefore be tested by sounding.

Osier Island.—The little island at the turn from Disenchantment Bay to Russell Fiord (see pl. VIII) is a low knoll constituted of the altered shales of the Yakutat formation. A rocky reef extends northwest from it, and a gravel spit, bare at low tide, joins it to the mainland. It has three faces, characterized by cliffs telling of active erosion by waves. The east face is turned toward Russell Fiord and receives the waves generated by southerly and southeasterly winds in a straight stretch of deep water nineteen miles long and from one and a half to two miles broad. A high cliff testifies to their efficiency, and so does the gravel spit just mentioned, to which they have brought not only pebbles but large boulders. The north face, which has a rock cliff of equal or greater height, is turned toward the ice cliff of Hubbard Glacier, 6,000 feet distant. The wind waves that reach it from Russell Fiord have only two miles at most in which to develop. Wind waves from the head of Disenchantment Bay, four miles distant, might reach it, and on rare occasions they probably do, but that part of the bay, being overlooked by the most active part of Hubbard Glacier, is ordinarily full of floating ice, which prevents the generation of such waves. Instead of wind waves the chief attack is by ice-fall waves. From four miles of ice cliff the bergs are breaking, and the cannon-like boom recording the sundering of one of the greater

blocks came to our ears every five or ten minutes. As each block fell, it started a series of circling waves, many of which were so large as to make breakers miles away, despite the damping effect of the floating ice. The breakers we observed on Osier Island were formidable enough to enforce much caution in landing, and the series from different ice falls followed one another so closely that there were few intervals of quiet.

The southwest side of the island is sheltered from all winds except westerly and, as it borders a cove which westerly winds would pack with ice, may never feel the force of wind waves. Ice-fall waves reach it from Turner Glacier after a journey of four miles, and by shorter, but deflected, courses from the Hubbard. Its shore cliffs are much lower than those of the other sides of the island.

In 1794, when Hubbard Glacier reached to Haenke Island, Osier Island must have been ice-covered and subject to glaciation, and it was not bared until more than half the subsequent wasting had been accomplished. It is therefore probable that the existing shore cliffs, estimated from memory as 25 to 30 feet high, have been carved out within a few decades. During part of this time the ice-fall waves reaching the north shore were more effective than now because the ice cliff was nearer.

From these various features, and especially from the comparison of the north and east shores of the island, it appears that ice-fall waves have very notable ability to erode coasts, an ability fairly comparable with that of wind waves. This fact is of value to the student of Pleistocene glacial lakes, as it enables him to understand the clear outlining of their coasts in cases where the indicated extent of the water surface is too small for the generation of important wind waves.

EXPLANATION OF PLATE XI

Map of Columbia Glacier

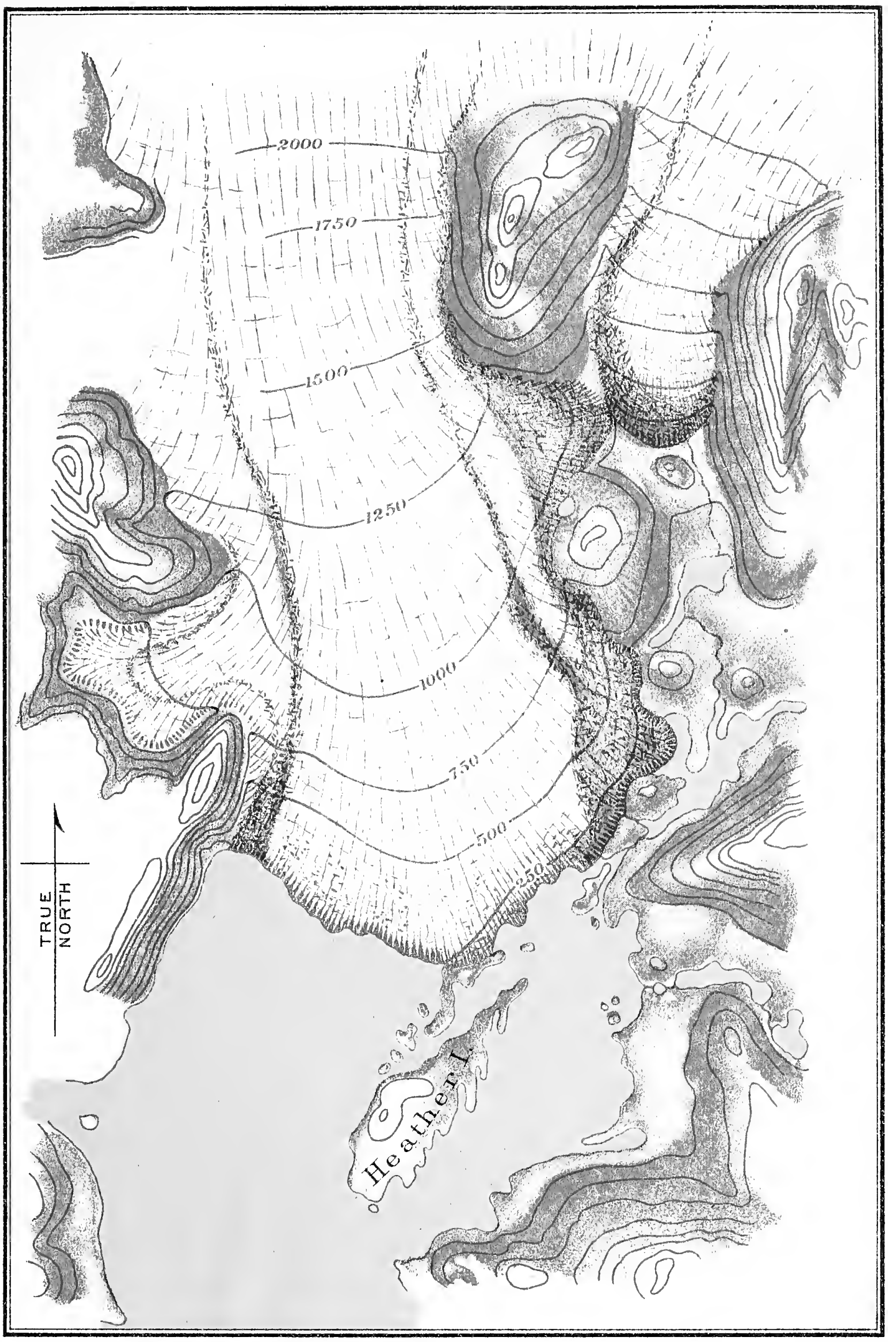
Columbia Glacier reaches the sea at the head of Columbia Bay, one of the numerous arms of Prince William Sound (see plate xiii).

Surveyed by G. K. Gilbert, June 25 to 28, 1899, with use of the plane-table, and with stations about the lower end of the glacier. Details about the nunatak are from notes by Charles Palache.

Drawn by Gilbert Thompson.

Contour interval, 250 feet. The bay is represented as at high tide. At lowest tide Heather Island is joined to islands north of it by mud flats, and extensive shoals are bared along the northeast coast.

The glacier is described on pages 71–81. It is pictured in plates ix and xii, and in figure 37.



MAP OF COLUMBIA GLACIER

SCALE

0 1 2 3 4 5 6

MILES

COLUMBIA GLACIER

Between Yakutat Bay and Prince William Sound we made no landing, and our course lay too far from shore for observations of value on the glaciers.

Prince William Sound is an extensive and intricate body of water, penetrating a mountain district. Its numerous islands and peninsulas are mountain peaks or ranges, and many of its inner arms and passages have the character of glacial troughs or fiords. Among the mountains of the mainland at the east and west are many small glaciers, and a great mountain mass at the north supports extensive névés from which magnificent ice rivers flow to its northern arms. It was my good fortune to be landed at the mouth of one of these ice rivers and, in company with Palache, Coville, and Curtis, to spend several days in its study. Many photographs were made and some mapping was done.

In June, 1794, this glacier was seen from the mouth of the associated bay by Whidby, one of Vancouver's officers. Vancouver says: "To the eastward of this is another bay of rather larger dimensions, with an island in its northeast corner, . . . terminated by a solid body of compact elevated ice, similar to that which has been before described . . . ; as they passed the eastern bay they again heard the thunder-like noise, and found that it had been produced by the falling of the large pieces of ice that appeared to have been very recently separated from the mass extending in vast abundance across the passage . . . , insomuch that it was with great difficulty the boats could effect a passage."[1]

The bay and island appear on a map in Vancouver's atlas (see fig. 42). The bay (without the island) is rep-

[1] A Voyage of Discovery to the Pacific Ocean and round the world, etc., Capt. George Vancouver, vol. v, London, pp. 316–317, 1801.

resented on a map prepared in connection with expeditions to Alaska under Glenn and Abercrombie, in 1898,[1] and the same map also indicates the presence of the glacier, but neither bay nor glacier is delineated with sufficient accuracy to serve as a record for future comparison. The name Columbia was given by the Harriman Expedition.

The general course of the glacier is southward, and its width in the lower ten miles is from three and a half to four miles. Its sources are distinct and were not seen, but beyond the tract covered by our map (pl. XI) it appeared to spread somewhat broadly, and the ice field affording its chief supply may send streams in other directions also.

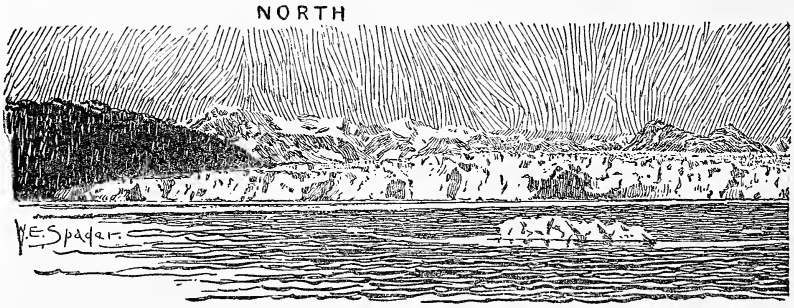
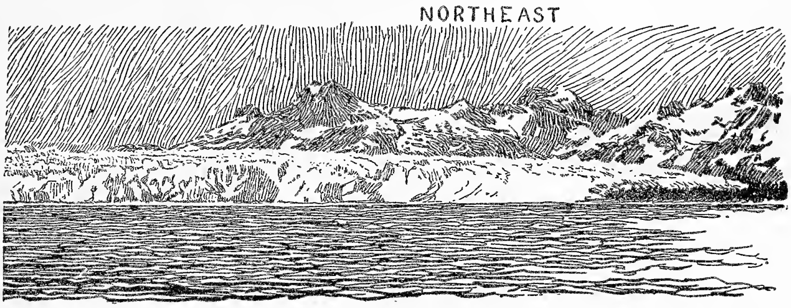


FIG. 37. PANORAMA OF COLUMBIA
Shows the western division of the front.

About nine miles from the sea it encounters an outlying mountain over 3,000 feet high, by which it is divided, the principal current passing to the west. The eastern arm descends steeply for three miles and terminates in a land-locked valley against a plain of glacial gravel. A subdivision of the western arm enters the same valley. In 1899 it barely touched the eastern arm, so that the mountain was wholly surrounded by ice and could properly be called a nunatak. Beyond this point the main stream flowed to the ocean, but the surface grades descended also toward lateral valleys, and there was waste all about

[1] Maps and descriptions of Routes of Exploration in Alaska in 1898. U. S. Geological Survey, 1899. Map No. 8.

the periphery. On the east side the ice rested against three low hills, beyond which were lakes supplied in part from its melting. In one place a lobe of ice touched one of the lakes. In a hollow on the side of one of the hills a lakelet was imprisoned by the ice, one of its shores being constituted wholly by the glacier. On the west is an embayment among high mountains, into which the ice sent a tongue two miles long, but there was no lake and no visible outlet for the water, which must have found its way to the sea beneath the body of the glacier. This feature is specially remarkable from the fact that the subglacial water could not follow the course of the ice, but for



GLACIER, FROM THE SEA.
From photographs by W. H. Averell, June, 1899.

several miles must either move in the opposite direction or take some independent route.

Columbia Bay, to which the glacier flows, is from four to five miles broad and is locally divided by a group of islands. The western arm, two and a half miles broad, is comparatively simple in outline and is probably deep. It received the principal discharge from the glacier, which spanned it from side to side with a cliff about 300 feet high. The eastern arm, irregular in outline and judged from the configuration of its shores to be comparatively shallow, was bordered by the glacier for a mile and a quarter, but the ice cliff was less lofty, and a comparison of its outline with other portions of the glacier showed

that the water controlled the form of the ice front to only a moderate extent. The principal island of the group, to which we gave the name Heather, is nearly three miles long and has an irregular surface, rising at one point to a height of 500 feet. It consists chiefly of rock. Several lower islands lie north of it, and the ice front rested against one of these for a space of 3,000 feet. The number of islands varies with the state of the tide, and it is possible that all are united at lowest tide.

Opposite the great nunatak were two medial moraines, one passing within a half mile of its base, the other lying about one mile from the opposite edge of the glacier. A central tract two miles broad was practically drift-free. Toward the end of the glacier this central tract broadened, the medials swinging toward the sides, until finally the white belt was three miles wide. As the medials diverged they also broadened, and they eventually merged with flanking moraines, so that near the end, especially on the east side, the areas of drift-covered ice were very wide. The marginal belt on the west, instead of continuing northward parallel to the medial with which it was associated, was seen to curve about into the western embayment, as indicated on the map, and a belt seen from a distance near the north edge of the embayment was supposed to be its continuation, a loop being made within the embayment. As the ice in the embayment descended toward the west, it is evident that the morainic loop could not at that time represent a line of continuous flow, for we can not suppose the ice to flow into the embayment on a descending course and then return on a parallel ascending course. It is therefore probable that the moraine was formed as a comparatively direct line of drift, following the course of the main ice current at a time when no current entered the embayment. The inference that a change has occurred naturally leads to enquiry as to the precise nature

EXPLANATION OF PLATE XII

Columbia Glacier, from Heather Island

The glacier is seen from the summit of the island. Its nearest point rests against a smaller island, joined to Heather Island at low tide. The part against the land, though steep, is not a cliff. An ice cliff faces the arm of Columbia Bay seen at the extreme right. At the left of the small island begins the long ice cliff shown in figure 37. At the extreme right, outlined against distant snow, is the hill from which the panorama in plate IX was photographed. See pages 71–81 and plate XI.

From a photograph made by E. S. Curtis, June 25, 1899. Negative NO. 302.

PHOTOGRAPH BY CURTIS

GILBO & CO

COLUMBIA GLACIER, FROM HEATHER ISLAND

of the antecedent condition of the glacier. On the one hand, the embayment may have been so full of ice that the surface gradient was outward; or, on the other, the glacier of the main valley may have had so low a surface that there was no tendency to overflow to the comparatively shallow side valley.

The first case implies snow accumulation in the embayment a few decades ago at a rate not since maintained, and would correspond to a general expansion of glaciers followed in later decades by contraction; but the relations of the ice to the forest, to be described presently, show that such contraction has not taken place. The second case implies a general expansion of the glacier as the important element of its later history.

Another medial moraine of the great ice field north of the nunatak passed just east of the nunatak and continued down the eastern arm of the glacier to its end, where it contributed toward the building of a great alluvial delta which was gradually obliterating one of the lakes.

At the western margin of its principal tidal cliff the glacier rested on a bank of drift at the level of low tide, and this bank extended eastward as a shoal, on which bergs were stranded, for several hundred yards from the shore. A bank also extended eastward from the island against which the ice front rested, constituting at low water a stony cape half a mile long near the foot of the ice cliff. These banks testify to a lingering, or lingerings, of the ice front near the position of its modern maximum, but it is not easy to estimate the duration of the lingering. The western bank is built in deep water, but may have been constructed rapidly, as the contiguous portion of the glacier is heavily charged with drift. The eastern bank margins a part of the glacier front carrying little débris, but occupies an arm of the bay which

was probably originally shoal. They may have been formed recently, or at some earlier epoch.

The drainage of the ice included several streams flowing eastward to the chain of lakes, and we noted two important streams from the western ice cliff. One of them issued from a cave at the water's edge near the western limit of the cliff, the other from a submerged and invisible tunnel near the middle of the cliff. The last mentioned was probably the largest of all the draining streams. It rose to the surface at the base of the ice cliff and flowed southward over the salt water, forming a broad lane of milky fresh water with a visible current and at times nearly free from floating ice.

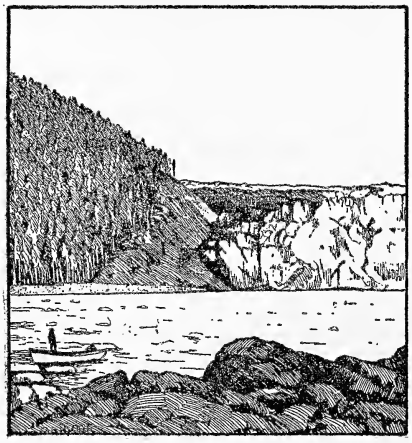


FIG. 38. WESTERN EDGE OF COLUMBIA GLACIER.

Shows barren zone and forest. From a photograph taken in June, 1899.

At most points the forest of spruce and hemlock approached close to the ice, its relation being similar to that observed at La Perouse Glacier. At the western margin of the main ice cliff, where the glacier crowded against a steep rock slope, there was a belt of bare rock, from 200 to 300 feet broad, between the ice and the forest (fig. 38). This belt was strewn with fragments, not only of rock but also of wood, and trees were freshly overthrown at the margin of the forest. At the time of its attack on the forest the ice must have been 100 feet deeper than in the summer of 1899, and it also extended farther southward, as shown by a push-moraine of rock at the water margin, 800 feet from the

ice front (fig. 39). A second push-moraine, less massive than the first, lay within it, being 160 feet from it at the water margin and elsewhere nearer to it than to the ice. On the island between the two ice cliffs there were also two push-moraines of recent date,

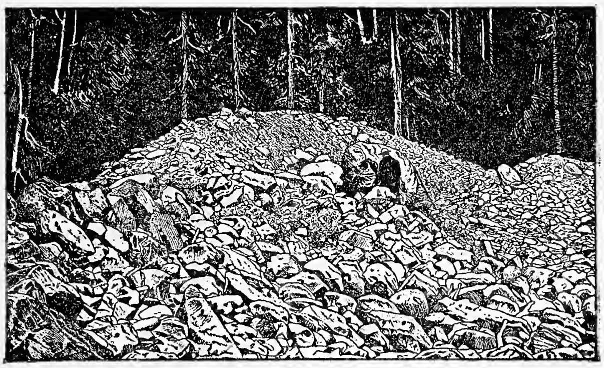


FIG. 39. PUSH-MORAINE, WEST SHORE OF COLUMBIA BAY.

the nearer being about 100 feet from the ice front, the farther from 300 to 500 feet. The latter was associated with overthrown forest trees, and included with its rocky

FIG. 40. FLUTED MORAINE AT EDGE OF COLUMBIA GLACIER.
Photographed in June, 1899.

débris not only tree trunks and branches but folds of peaty soil. The tract between the nearer push-moraine and the ice was in places occupied by an old mo-

raine surface over which the ice had advanced, and this surface was elaborately fluted in the direction of ice motion, the corrugations having a vertical magnitude of several feet (fig. 40). In one instance it was seen that a large bowlder in the underlying drift had impressed its form on the ice, preserving in its lee a train of drift of the same cross-section, which constituted a ridge, and it is probable that the other flutings were of the same character. As these details in the configuration of the drift surface would be quickly obliterated by frost and rain, their exposure must have been very recent. Probably the advance creating the push-moraine and the subsequent melting which laid bare the ice-molded drift had taken place within one or two years.

On the mainland at the east the same phenomena were observed, with the exception of the fluted drift surfaces. There was an inner push-moraine, chiefly or wholly of drift and running parallel to the ice margin. There was an outer push-moraine, less regular in its distance and associated with disturbance of the forest and the meadow peat (fig. 41).[1] In the tract between the two many prostrate trunks were seen, showing that in places the front of the forest had been crowded back several hundred feet. Many of the trees that were overturned but not overridden, retained their bark, branches, and even minor twigs, but the leaves had fallen. On disturbed forest soil Coville found three young spruces which had grown since the catastrophe. In each case the age, as shown by rings of growth, was seven years. The date of the ice maximum was therefore not later than 1892 and may have been that year.

[1] The view in fig. 41 is toward the northeast — along the front of the push-moraine. A little of the steep face of the glacier is seen at the left. At right is a tract of undisturbed bog.

FIG. 41. MORAINE MARKING ATTACK BY COLUMBIA GLACIER ON FOREST AND BOG.

The overturned forest trees associated with the push-moraines on the eastern and western shores of the bay and on the island, exhibited the same general appearance of recency, and there can be little doubt that they were disturbed at the same time. They demonstrate a temporary increase in the size of the glacier, not of precisely the same amount at all points, but of the same order of magnitude. Previous to that expansion the glacier had been smaller during a period at least sufficient for the growth of the overturned trees. The evidence from forests and push-moraines does not show whether the ice during this epoch stood continuously near to the forest or was subject to wide oscillations in extent; but the bending of the moraine belt on the back of the glacier into the western embayment (page 73) gives strong support to the view that the recent maximum was preceded by an important minimum.

No attempt was made to estimate the age of the trees by counting rings of growth, but the forest had the characteristics of maturity, and the time required for its production could hardly have been less than two or three centuries. The mountain side just west of the glacier, rising steeply to a height of 2,000 feet, is clothed with a luxuriant growth from the push-moraine up to about 1,500 feet. Many of the trunks are three or four feet in diameter, and among them lie prostrate logs in a state of decay. Upon the islands, and on the lowland near the east margin of the glacier, the trees are somewhat smaller, but the many dead trunks standing among them indicate that they are mature, and their term of life may be as long as that of their western neighbors.

A further item of information as to variation, albeit somewhat indefinite, may be derived from Vancouver's map. It is not sufficiently precise to afford identification of any topographic detail of the bay except Heather Island

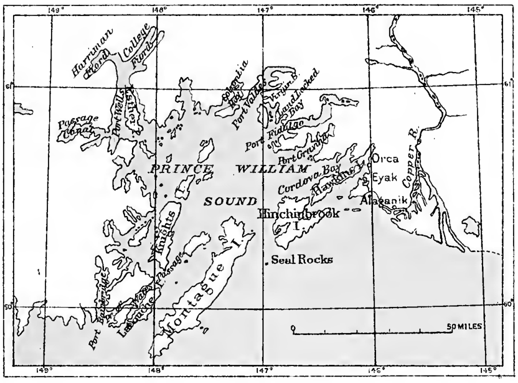
EXPLANATION OF PLATE XIII

Upper Figure.—Prince William Sound

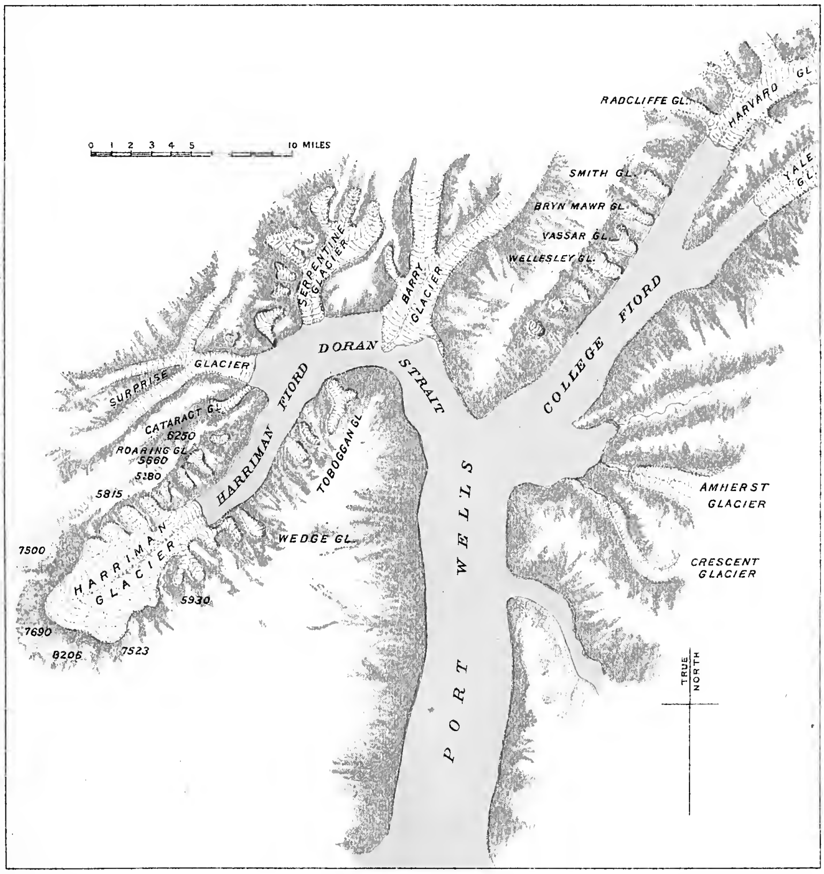
An index map of the sound, showing positions of Port Wells and Columbia Bay. Based chiefly on United States Coast Survey chart no. 3091.

Lower Figure.—Sketch of Port Wells

Surveyed by Henry Gannett, June 26 to 29, 1899. Drawn by Gilbert Thompson. Details about Amherst Glacier are in part from the map of an expedition under Captains Glenn and Abercrombie, U. S. A.; and use was made also of photographs.



PRINCE WILLIAM SOUND



A. HOEN & CO. BALTIMORE.

SKETCH OF PORT WELLS

(see fig. 42), but the narrowness of the strait represented between the island and that portion of the coast said to consist of ice, indicates the impression of the explorers that the ice wall stood not very far beyond the island; and this view is supported by the statement already quoted that the island was in the "northeast corner" of the bay. It seems reasonable to infer that the glacier was not much smaller in 1794 than in 1899; and that if the features of the embayment prove a recent and important minimum, that minimum occurred in the nineteenth century.

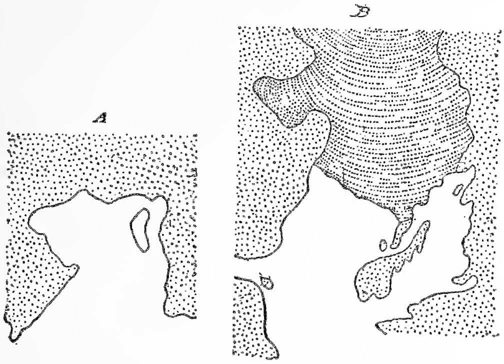


FIG. 42. OUTLINES OF COLUMBIA BAY.
A, enlarged from Vancouver's map (1794), which does not distinguish the glacier from other parts of the land. *B*, reduced to same scale from plate XI, showing relations of sea, glacier, and land in 1899.

COLLEGE FIORD

While our boat party was occupied with Columbia Glacier the main division of the Expedition visited the northwestern arm of the sound, called Port Wells, where important contributions were made to geographic knowledge. College Fiord, the right branch of Port Wells, was explored more thoroughly than ever before, and the left branch, Harriman Fiord, was discovered as well as explored. The fiords were mapped by Gannett, and their beautiful and imposing series of glaciers were photographed by half a dozen cameras. After the ship had picked up my party in Columbia Bay, it returned to Harriman Fiord for Gannett and Muir, and I was thus enabled to sail past several of the Port Wells glaciers, but the following description is chiefly at second hand. Many of the best

photographs of the Port Wells glaciers are reproduced by photogravure to illustrate the narrative of the Expedition, and, to avoid needless repetition, I have selected for my own use only the views most important in connection with my text, but I shall refer freely to the plates of volume I.

College Fiord is from two to three miles broad and about twenty miles long, trending north-northeast and south-southwest. Near the south end, where it joins the main body of Port Wells, there is a bay on the east side overlooked by two non-tidal glaciers. The larger of these was called Amherst by the Expedition, the name being given in honor of an American college. Somewhat north of the middle the fiord sends an arm to the northeast, and this arm receives a large tidal glacier, the Yale. At the head of the main fiord is the Harvard, also a large tidal glacier. Several branches of the Harvard were visible from the ship, and that next to the ice front on the northwest was named Radcliffe. A series of glaciers on the northwest side of the fiord resembled the Radcliffe in general character, and four of these received names — Smith, Bryn Mawr, Vassar, and Wellesley.

Amherst Glacier was passed by the ship at some distance, and its features are known chiefly through the photographs secured by Merriam (pl. XIV). It is fed by névés in full view from the fiord, and approaches the sea in a short, broad stream which at first descends steeply and afterwards more gently. The habit of the lowland lying between the glacier and the ocean indicates that it is built of morainic material. Near the sea is a belt of timber, but this is separated from the ice by a barren tract similar to that about Davidson Glacier. A barren zone several hundred yards broad is seen to flank the glacier on the southwest, and a similar zone borders its companion, Crescent Glacier. These features doubtless indicate shrinkage in modern times, the change having been of moderate

EXPLANATION OF PLATE XIV

Amherst and Crescent Glaciers

The Amherst Glacier is at the left, in the view, the Crescent at the right.

These glaciers are on the east side of College Fiord, at its junction with the main body of Port Wells. Their position is shown in plate XIII. See pages 82–83.

From a photograph made by C. Hart Merriam, June 26, 1899. Negative No. 124 of the United States Biological Survey.

PHOTOGRAPH BY MERRIAM

GILBO & CO

AMHERST GLACIER   CRESCENT GLACIER

amount, although greater than in the case of La Perouse and Columbia glaciers. The Crescent is comparatively narrow, and approaches the sea with a higher grade. A curve in its trough conceals its upper course.

The Yale drains a larger area and receives a number of tributaries. The front of the cliff is wide, but of moderate height, and a blackening, west of the middle, by englacial drift suggests that a rock knob may lie near the surface, ready to develop into a nunatak or island if the glacier shall diminish. The trough in which it lies is forested along the water edge on both sides for the greater part of the distance from the main fiord to the glacier, but barren in the immediate vicinity of the glacier. There are straggling trees high on the valley wall at the end of the glacier, but they do not come down close to the ice. An excellent photograph of the glacier is reproduced at page 128 in volume I. It is enlarged from negative 113, U. S. Biological Survey. A nearer view of the eastern part of the front (fig. 43), although lacking detail at the critical point, may serve a purpose for comparison when the glacier shall be revisited. It shows a small tributary, cascading from a hanging valley near the end of the main glacier.

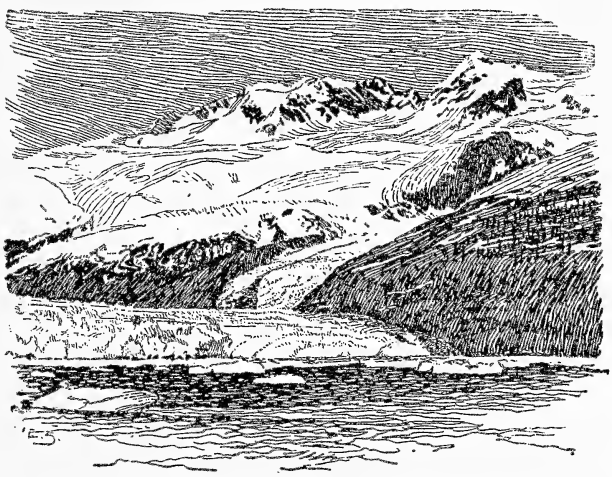


FIG. 43. EAST PART OF FRONT OF YALE GLACIER.
Shows position of front in 1899 in relation to a tributary from the east.

The Harvard Glacier is by far the greatest discharging to the fiord. Only a few miles of it are visible from the sea, as the main trunk, traced backwards, curves to the right and disappears. So far as visible it is of low grade, its slope being gentler than that of any other we saw except the Muir and Columbia; and this feature, taken in conjunction with the notable height of the cliff in which it terminates (350 feet), indicates great depth of the ice stream and a remote source. The large number of medial moraines tells us that it has many branches, and five are visible from the sea. One from the southeast joins within a mile or two of the end, and the other four come from the northwest and north. All have steep grades in approaching the main trunk, but two at least show gentler grades at higher altitudes. The Radcliffe joins the Harvard so close to the water front that it does not become fully merged with the greater stream, but merely coalesces at one edge on its way to the sea. A conspicuous medial moraine of the Radcliffe maintains its high declivity quite to the water's edge, and the cliff where the Radcliffe ends is notably lower than the confluent cliff along the front of the Harvard. The next tributary is likewise characterized by a strong medial moraine, and the branching from which this arises can be seen a short distance back from its junction with the Harvard. The photographs show no trees in close proximity to the Harvard. The point of land at the branch in the fiord five or six miles to the south is forested, and this forest follows the coast for some distance toward the glacier, but stops several miles from its front. The opposite coast is reported free from trees at the water's edge for eight or ten miles, but at an altitude of several hundred feet the trees approach the glacier. These relations, while they do not show whether the glacier is now waxing or waning, indicate that its length has been several miles greater at a

FIG. 44. HARVARD GLACIER, JUNE, 1899.

The observer is on the water, about seven miles from the glacier. Its tidal cliff is more than two miles wide, and is 350 feet high at the great medial moraines. The head of the glacier, far distant at the right, is not visible. Of the four tributaries visible the only one which has received a name is the Radcliffe, at the extreme left.

period so recent that the forest has not yet reoccupied the abandoned ground.

As the Harvard has recently retreated more than its neighbors, and as its velocity is presumptively high, its future changes will have special value as indices of the local variations in the conditions of glaciation, and the record of its magnitude in 1899 is therefore important. Unfortunately the party did not approach it closely, and the photographs are deficient in detail at critical points, but they will enable the future observer to recognize any change of important magnitude. The best available data for 1899 are contained in Curtis's photograph No. 273, reproduced at page 72 in volume I. The east end of the frontal cliff, as there shown, is not far (between 1,000 and 2,000 feet) from the apex of a delta, or alluvial fan, built by the stream from a small hanging glacier. It is also seen that the eastern part of the glacier cascades about a half mile from the front, dropping so low that its tidal cliff has only half the height of that of the central part. At the west the relation of the Harvard to the Radcliffe is manifestly sensitive to the influence of advance or retreat. A moderate recession would separate the two glaciers; an advance would deflect the lower part of the Radcliffe medial moraine into parallelism with the Harvard medials (see fig. 44).

Smith Glacier reaches the fiord three or four miles from the Radcliffe, and is of the same order of magnitude. Fed by several tributaries among the crests of the range, it gathers in a high mountain valley and then descends in magnificent cascades down the mountain front to the sea. In the last part of its course it has scarcely any valley, the outer surface of the ice being practically flush with the face of the mountain; and there is no flattening of its profile as it reaches the water. Though its lower slope is so seamed by crevasses as to exhibit a mere congeries of

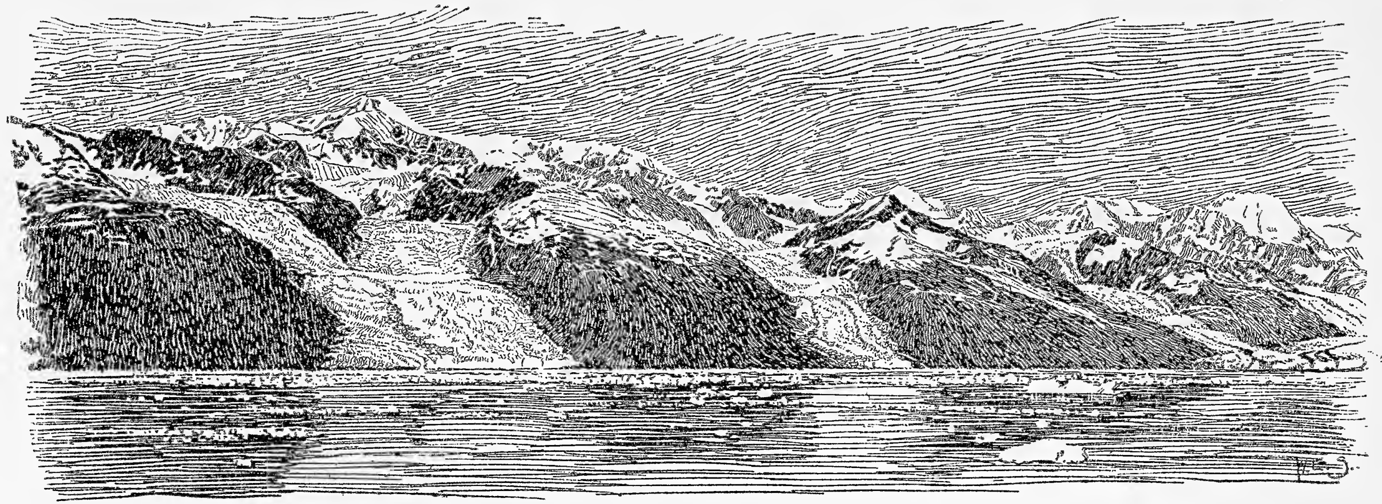


FIG. 45. WEST SIDE OF COLLEGE FIORD.

College Fiord is the northern arm of Port Wells, a division of Prince William Sound. See pl. XVIII. The view is from the water of College Fiord. At the left is Bryn Mawr Glacier, then the Smith, and then the Radcliffe, joining the Harvard. Characteristic features are the step-like ice cascades, and the shallowness of the lower valleys of the glaciers.

pinnacles, two lines of medial moraines are distinctly traceable, each partitioning off a fourth part of the ice stream at the side.

The Bryn Mawr, next south of the Smith, is somewhat larger. Its two main branches, gathering in mountain valleys not well seen from the sea, become visible in twin cascades, and then, uniting their streams, make a second leap to the sea. As tide is reached, there is a tendency to flatten the profile, and the central portion of the stream becomes nearly or quite horizontal for a few hundred feet before breaking off in the terminal cliff.

Next in the series comes the Vassar, parallel to the Smith and Bryn Mawr and exhibiting a similar series of cascades, but of smaller size and less direct in its course. It is cumbered, especially in its lower part, by rock débris, and close inspection was necessary to determine the fact that it was actually tidal.

The Wellesley, last of the tidal series, flows with gentle grade through a mountain trough joining the fiord at right angles, and then cascades to the sea, into which it plunges without notable modification of profile. Beyond it are small glaciers occupying alcoves on the mountain front but ending far above the water.

The Bryn Mawr, Smith and Radcliffe are represented in fig. 45, the Bryn Mawr alone in the frontispiece, and the Wellesley in a plate at page 122 of volume 1, from a photograph by Merriam (No. 121, U. S. Biological Survey series). The Bryn Mawr was photographed at shorter range by Curtis (No. 276 A), but the view has not been reproduced.

In the intervals between the tidal glaciers just described there is no forest at the water's edge, and the photographs reveal none at higher altitudes; but a little farther south the coast is forested, and the trees climb up a few hundred feet on the moraine heaps under the hanging glaciers.

They are separated from the ice, first by a broad belt of alders, and then by a barren zone. As the spruce forest in College Fiord nowhere stands close to the ice, but is separated by a barren zone, it seems fair to assume that the ice has occupied this zone so recently that the period since its shrinkage has not sufficed for reforesting; but no facts are recorded tending to show the nature of the changes immediately preceding our visit.

The four tidal glaciers on the northwest side of the fiord, and four branches of the Harvard reaching it from the same mountain range, show a remarkable agreement in certain general features of profile. Near their débouchure they descend in one or more steep cascades through a vertical space of 1,700 to 3,000 feet, and back of these cascades their slopes are comparatively gentle. Their upper valleys are deeply incised, but their lower valleys are shallow, barely sufficing to hold the ice streams, so that the faces of the glaciers are nearly flush with the general face of the fiord wall. These features indicate that the principal work of ice sculpture was performed when the trunk glacier filled the fiord to a level somewhat above the line of cascades. It was then that the fiord wall received its smooth contours, and much of the general excavation of the fiord may have been performed at the same time. The tributary ice streams from the side carved shallower troughs, adjusted to their needs, and were prevented from excavating deeply at any point because the great trunk glacier gave them a high base-level of discharge. These tributary troughs will receive further consideration in the chapter on Pleistocene glaciation.

HARRIMAN FIORD

From the bend where it is joined by College Fiord Port Wells extends only three or four miles northward and is reduced in width. Its trough then swings quickly

to the west and southwest and is continued twelve miles farther. At the apex of the turn a large glacier (the Barry) protrudes from the northern shore, reducing the waterway to a narrow strait. The portion above the strait, having been discovered by the Harriman Expedition, was named Harriman Fiord. The general width of the fiord is from two to three miles. Considered as a mountain trough, it branches near the middle, but the western branch is almost wholly occupied by a glacier. Its walls are everywhere high, and it is in fact a secluded pocket among the mountains. All about are glaciers, of which four are of large size and six reach the sea.

Barry Glacier (fig. 46), at the entrance to the fiord, approaches from the north-northeast. Its low grade indicates a distant source, but the source was not seen, as its upper valley was concealed by mist. Unfortunately the map data secured do not afford an accurate determination of the dimensions of its end, but it impressed the beholder as one of the largest ice rivers of Port Wells. Its peculiar relation to the fiord causes it to be swept by the passing tide and prevents the accumulation of icebergs about its front, but the same relation exposes it to exceptionally rapid melting by the sea, and the conflict of ice current

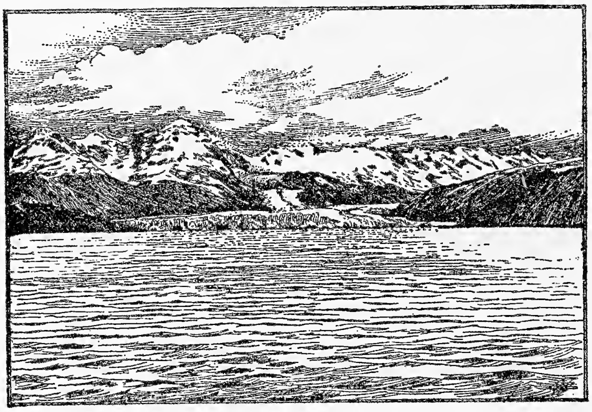


FIG. 46. DISTANT VIEW OF BARRY GLACIER, 1899.

The glacier comes from behind the dark hill at the right. The visible tributary descends by two cascades. Doran Strait lies between the glacier front and the sloping point of land at the left.

with tidal current must be active. The forward flow of the ice tends to narrow the strait, and this constriction, by increasing the speed of the tide, enhances the melting power of the water. The fact that the glacier was able to occupy two-thirds of the width of the fiord indicates that its forward movement was strong.

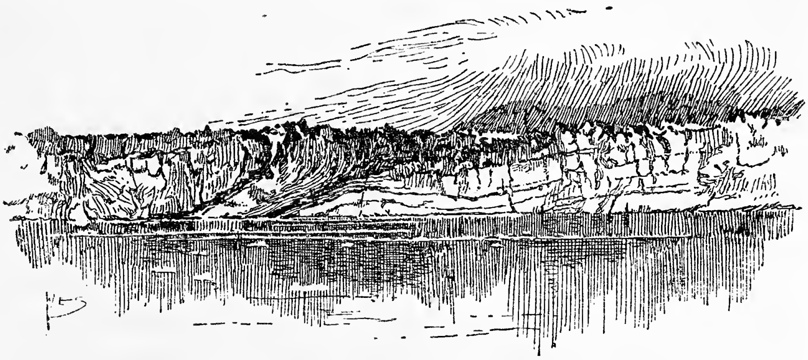


FIG. 47. PART OF FRONT OF BARRY GLACIER.

Showing the relation of a medial moraine to a great oblique dirt band. Photographed by E. H. Harriman from the ship, June, 1899.

Its moraines were of small relative importance, but a belt along the western margin was darkened by drift and there were two medials. One of the latter, exhibited in section in the face of the cliff, was seen to be the surface outcrop of a sheet of drift-charged ice which extended obliquely downward, passing under the western portion of the stream (see fig. 47).

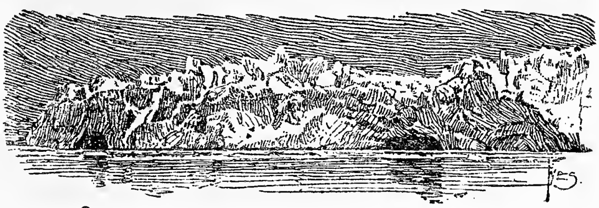


FIG. 48. CAVES IN FRONTAL CLIFF OF BARRY GLACIER.
From a photograph by W. R. Coe.

The cliff was further diversified by a number of caves at the water's edge, supposed to be the mouths of englacial streams.

Connected with the eastern edge of the ice was a long, narrow tongue attached to the shore (fig. 49), evidently a remnant left by the glacier at some very recent date when its front was more extensive. As this strip was not protected by gravel, it must have been wasting rapidly, and the period of its separation may have been only a few months. I was in doubt whether to ascribe it to a progressive shrinkage of the glacier or to seasonal variation.

FIG. 49. EAST PART OF FRONT OF BARRY GLACIER.
Showing associated remnant of stagnant ice. From a photograph by D. G. Inverarity.

On the same coast the forest did not approach the glacier closely at the water line, but passed above it, leaving a barren zone several hundred feet broad. The common boundary of the barren zone and forest was so well defined as to indicate that it represented a former limit of the ice, but there were no overturned trees. If the forest ever occupied the barren zone, and was there destroyed by an advance of the glacier, the occurrence was so long ago that the overturned tree trunks had disappeared through decay. The portions of the forest nearest the ice included no trees of large size, but as there were many standing dead trunks it is probable that the growth was mature and that the small size of the trees indicated merely conditions un-

favorable to luxuriant growth. Translating these facts into terms of glacial history, it seems probable that the Barry had been, at some time within the century, somewhat larger than when we saw it, but that it had not for a series of centuries exceeded the limit marked out by the neighboring forest. If any change had occurred within the last year or two it was of diminution.

The opposite wall of the fiord is forested down to the water's edge, and it is thus shown that no recent advance of the glacier has carried it completely across the channel.

Next west of the Barry is Serpentine Glacier, coming down to the fiord from the north. It is a broad stream, of low grade, fed by four or five tributaries descending steeply from amphitheaters in the encircling mountains. Though it reaches the sea, it yields few bergs, but is building a moraine barrier along most of its front. Its medial and lateral moraines are conspicuous, especially the northern lateral. Like the Turner and Reid, it seems to rest on a valley floor considerably above the floor of the fiord to which it is tributary. Its most westerly branch (fig. 50) heads in a high valley not fully commanded from the fiord and falls to the main glacier in two fine cascades. At the level of the upper cascade, 3,000 to 4,000 feet above tide, are three hanging glaciers, perched in alcoves of the valley wall where it curves to join the wall of the fiord.

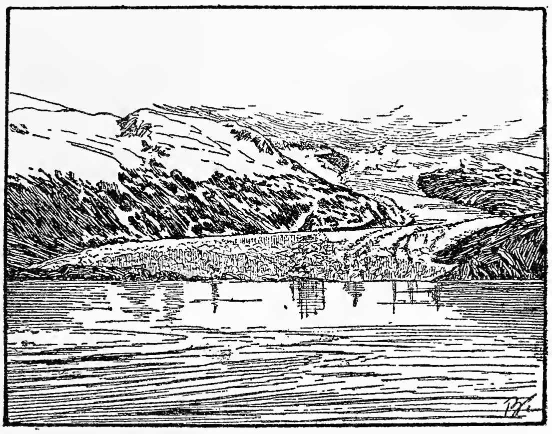


FIG. 50. SERPENTINE GLACIER.
The main body of glacier lies behind the nearer hill at right.

The only observed fact bearing on its recent history of change is the absence of trees from the valley walls near it.

Two of the hanging glaciers are shown, at the left, in figure 50. The cascading tributary and other branches of the Serpentine appear at page 124 of volume 1, in a plate reproducing photograph No. 292 of Curtis's series.

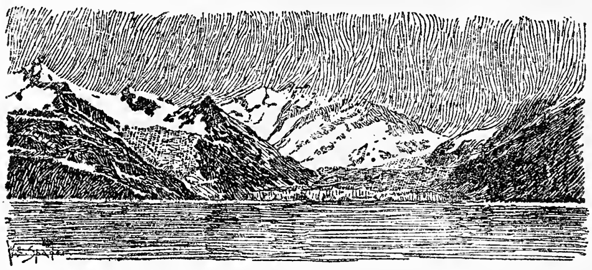


FIG. 51. SURPRISE AND CATARACT GLACIERS.

Surprise Glacier (at right) has its source in a valley system beyond Cataract Glacier.

Surprise Glacier reaches the fiord from the west, and occupies a deep and long branch valley. Its sources were not visible, being concealed by the curvature of its valley, but its moderate grade and the lofty ice cliff in which it ends, mark it as an important ice river.

Its near neighbor, Cataract Glacier, occupies a narrow and lofty mountain trough, from the end of which it sends a steep, tapering tongue down to the sea. It is intermediate in type between the hanging glaciers of the Serpentine valley and the cascading glaciers of the west wall of College Fiord.

The valley containing Harriman Glacier is a continuation of the main trough of the fiord and holds the same general southwest trend. The glacier curves toward the west and then toward the south, disappearing from view at a distance of nearly ten miles. As the most distant portion seen has a gentle slope and lies far below the bordering mountains, it is probable that the sources are still several miles beyond. Its general width is about a mile and a half, but its high-grade tributaries are so thick-

EXPLANATION OF PLATE XV

Harriman Glacier

The *Upper Figure* shows the south end of the frontal cliff of the glacier and adjoining parts of the valley wall. The main part of the glacier lies outside the view at the right (see plate XIII). At the left a tributary glacier descends from the mountain, and there are glimpses of other tributaries farther to the right. The visible part of the Harriman Glacier is probably a motionless remnant, left clinging to the valley side by a slight retreat of the central part of the frontal cliff. See pages 94–96.

From a photograph made by D. G. Inverarity, June 27, 1899. Negative no. 286 of the Curtis series.

The *Lower Figure* shows the north end of the frontal cliff and adjoining parts of the northwest wall of the valley. High on the mountain are two hanging valleys, each with a small glacier. See pages 95 and 119.

From a photograph made by D. G. Inverarity, June 27, 1899. Negative no. 285a of the Curtis series.

HARRIMAN GLACIER
SOUTH END OF FRONTAL CLIFF

PHOTOGRAPHS BY CURTIS

HARRIMAN GLACIER
NORTH END OF FRONTAL CLIFF

set as practically to coalesce, especially on the southeast side, giving a broad expanse of nearly continuous ice and névé. This expanse, fully commanded from the water, makes the view of the glacier a most impressive spectacle.

The visible moraines are few and unimportant, but the presence of much embedded drift is suggested by a detrital bank on which the eastern edge of the ice is seen to rest at the front. Above this bank the frontal cliff is low and irregular, but elsewhere it is lofty, ranging in height from 200 to 300 feet. From such a cliff an active discharge of bergs might be assumed, but our parties encountered only a moderate quantity of floating ice near the head of the fiord.

The glacier is not closely approached by forest growth, but shrubs were seen on the shore of the fiord within a few hundred yards of the ice. If the ice is diminishing, the recent retreat of the glacier front would appear not to have been rapid. The condition of the front in June, 1899, is recorded in a series of photographs. Two of these, reproduced in plate XV, show the ends of the frontal cliff, where the ice adjoins the valley walls, and will be serviceable for future comparisons with reference to advance or retreat. A third (Curtis negative NO. 291), published in volume I at page 74, gives a distant view of the glacier and its southeastern tributaries; and a fourth (Harriman negative NO. 98), appearing in volume II at page 262, gives the glacier and its surroundings from a somewhat nearer point.

Some of the minor glaciers associated with the Harriman occupy elevated valleys far above the main trough, and these upland valleys probably constitute a system initiated at an earlier epoch, when the fiord was flooded with ice to a great depth. Illustrative examples are afforded by two hanging glaciers overlooking the lower

part of the Harriman from the northwest (pl. xv). No measurements were made, but it is evident from an inspection of photographs that the heights of such features in this neighborhood are approximately the same as in the vicinity of Serpentine and Surprise glaciers, and it is possible that a number of minor glaciers observed on both sides of the fiord constitute with these a general system. Roaring Glacier, between the Cataract and the Harriman, owes the peculiarity suggesting its name to an abrupt change of grade. From a comparatively gentle slope it passes to one so steep that loose masses find no lodgment, and as its movement steadily projects its end beyond the point of inflection, fragments of ice break away and tumble down the steep incline, to gather in a heap far below, where they lie until melted.

The condition of extreme glaciation to which these phenomena point does not belong to the series of modern changes, and will be referred to again in the chapter on the Pleistocene history. Were it of comparatively recent date the fiord would now be destitute of trees, but such is not the fact. It is true that the slopes are bare in the immediate vicinity of the glaciers, and that the valley walls enclosing the greater glaciers — the Barry, Serpentine, Surprise and Harriman — support no trees, but the lower parts of the fiord walls are elsewhere covered by a hemlock forest.

As to the proper interpretation of the peculiarities of forest distribution the case is not altogether clear. In other localities there has seemed good reason to ascribe absence of forest to recent occupation by ice, but here there is a sort of transition from forest to barren which suggests climatic limitation. In the zone of transition the trees are not young and vigorous, as when invading newly-acquired territory, but scrawny and ill-favored, as though struggling desperately against the attack of hostile condi-

tions. In the accompanying illustration, representing the edge of the forest nearest to Harriman Glacier, the rareness of branches on the side toward the water suggests that winter fogs driven landward overwhelm the boughs with loads of ice.

FIG. 52. HEMLOCKS BORDERING HARRIMAN FIORD.

GREWINGK GLACIER

West of Prince William Sound we saw glaciers in abundance — on Kenai and Alaska peninsulas and on Unimak and Unalaska islands — but only one was visited or approached so closely as to permit the making of observations worthy of record.

The Grewingk Glacier is one of a series descending the northwest slope of the mountainous Kenai Peninsula. It was mapped by Dall in 1880, and revisited in 1895, when he made accurate note of the position of the ice front with reference to an object on the southern wall of the valley. In 1899 he accompanied me to the edge of the glacier for the purpose of pointing out this object, and I made a few photographs and other observations to aid in the recognition of future changes.

The glacier descends with moderate grade from a high névé, and maintains in its lower part a width of one and one-third miles. Its front is three miles from the sea, the interval being occupied by a gravel plain. For half the

distance the plain is bounded at the sides by rock walls, continuous with those containing the glacier, but these end at the general line of coast, and the plain flares beyond them as a low, broad cape. It is in fact a delta of glacial detritus, filling the lower part of the glacier trough and encroaching on the bay. The building of the plain is rapid. Its upper part was almost barren, as we saw it, only supporting enough scattered young spruces to show that their spread was not absolutely prohibited by soil or climate. Lower down were plantations of vigorous young cottonwoods, but no mature groves were seen. Bordering lands of earlier origin are covered by spruce forest, and in places the growing gravel deposit was evidently invading the forest, overwhelming the undergrowth and burying the roots of large trees so that they languished and died. I was impressed with the fact that the quantity of rock waste discharged by the glacier was much greater than would normally be discharged by a stream of water draining a similar area.

The glacier bore no large moraines, and its generous output of rock waste must have been supplied chiefly by the englacial drift. The visible belt of this drift was broad at one or two points, but in general so narrow as to give the impression that the base of the ice lay considerably below the level of the gravel plain. The ice front was steep, probably ranging from 20° to 30°, and impressed Dall as much steeper than in 1895. It was decidedly steeper than the front of Hidden Glacier and the north front of the Hugh Miller, observed a month earlier, but less steep than non-tidal portions of the Columbia. If the correlation of high and low frontal slopes with advance and retreat is well founded, the Columbia and Grewingk glaciers were advancing in 1899 and the Hidden and Hugh Miller were retreating. If the slopes are related to the direction of the sun, those toward the south

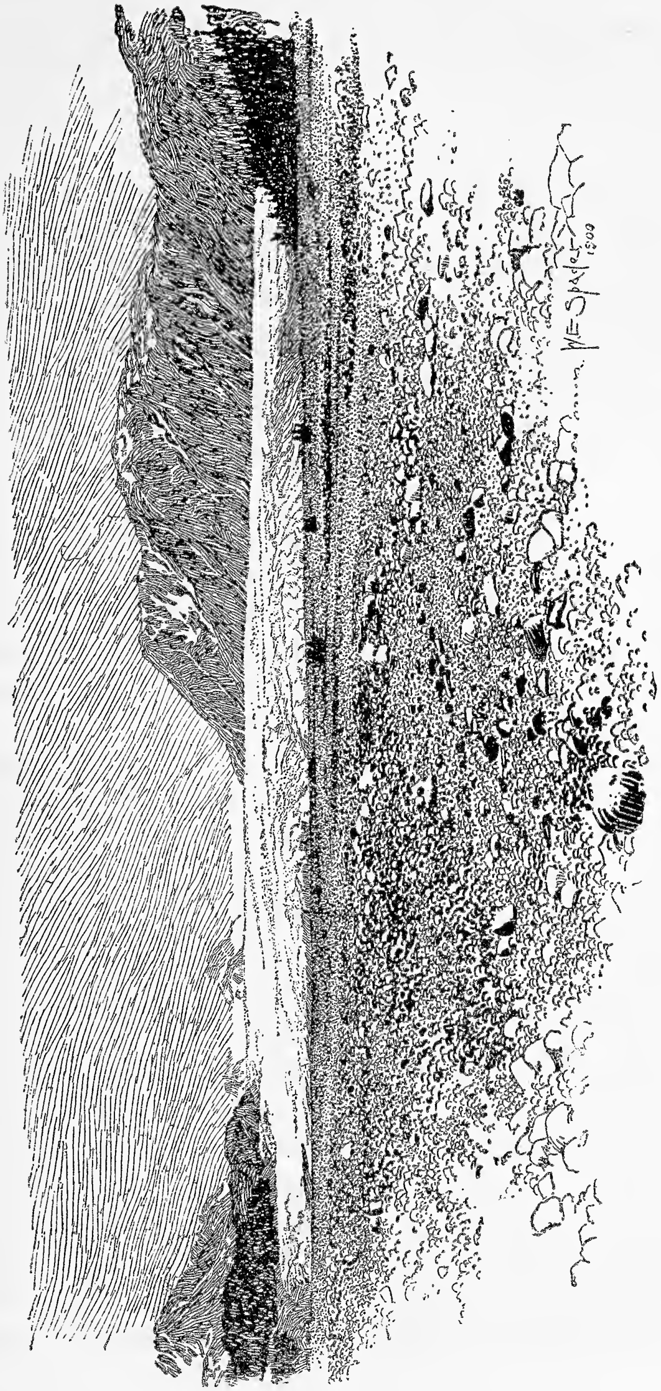


FIG. 53. GREWINGK GLACIER, GENERAL VIEW FROM THE WEST IN 1899.

The north edge of the ice (at left) is seen to be separated from the forest by a belt of bare rock. The corresponding feature on the south is shown in figure 54.

are steeper than those toward the north. Close to the ice front the plain was interrupted by a low ridge of gravel (see fig. 54), a push-moraine associated with some small

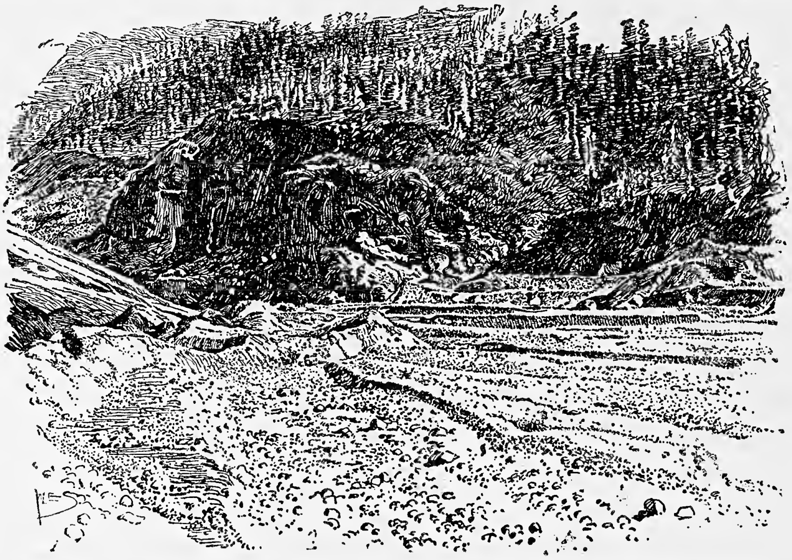


FIG. 54. SOUTH WALL OF VALLEY AT FRONT OF GREWINGK GLACIER.

and recent advance of the glacier, and possibly a phenomenon of the annual oscillation of the front. Farther out on the plain the course of a much larger moraine was marked by a crescentic line of mounds and short ridges, remnants of a once continuous morainic rampart that had been breached at many points by streams from the glaciers. I judged that this also was a pushed-up ridge, resulting from a plowing of the gravel deposit during a rapid advance of the glacier. It was not strictly parallel to the ice front in 1899, nor to its outline as mapped in 1880, but was more convex downstream. Its middle part was 2,600 feet from the glacier in 1899, and its most southerly remnant 800 feet. In 1880 Dall observed a considerable amount of ice under the sand and gravel of these mounds, and I noted many kettle-holes resulting from recent melting of ice remnants under the gravel

plain inside the crescent. It is therefore probable that the advance occurred only a few decades ago.

Between 1880 and 1895 the ice retreated through a space estimated by Dall at 250 feet. Between 1895 and 1899 the portion of the front adjacent to the south wall of the valley retreated 350 feet. It happened that all of the observations were made in the same month, so that the recorded changes were independent of seasonal fluctuations.

Figure 54, representing the south wall of the valley at the front of the glacier, shows the position of the ice on July 21, 1899. The gravel plain and the inner push-moraine occupy the foreground. At the extreme right a low boss of rock juts from the valley wall into the gravel plain, and just to the left of it is a large boulder resting on a drift terrace. On July 29, 1895, Dall found barely space to pass between the glacier and this boulder.

The same view shows the barren zone of the valley side and the lower limit of the forest, and the corresponding features for the north side of the glacier are seen at the left in the general view of the glacier, figure 53. At the south the line of forest was about 200 feet above the edge (1899) and descended westward to the gravel plain in 800 feet. For some distance below the line scattering young spruces and other bushes were seen, and even within the tract uncovered since 1895 a few alders had started. Nevertheless, the line of forest was clearly defined, being the lower limit of mature trees, dead trees, and accumulated humus. Though the line was unquestionably caused by an advance of the ice, it was not marked by heaps of overturned trees, as at the La Perouse and Columbia glaciers.

From these various phenomena a number of inferences may be drawn: (1) For several centuries — the age of the forest, including its dead trees — the glacier has not extended beyond the lower limit of the forest; that is, it

has not very greatly exceeded its present size. During that period it may or may not have been much smaller than now. (2) During the latter part of that period the glacier advanced to the forest line and then retreated. This maximum probably occurred as much as fifty years ago — to allow for the disappearance of the overturned trees — but could hardly have been so early as the beginning of the nineteenth century, else there would be larger spruces below the forest line. (3) Several decades ago there was a maximum, affecting especially the central part of the glacier, and retreat from this was still in progress to the close of the century.

There was little difference in the extent of the two maxima, and although their separateness was not doubted during my visit, it now seems to me possible that the two were identical. One was inferred wholly from the features of the valley wall, and the other wholly from the frontal moraine. The straggling of young spruces below the forest line afforded so strong a contrast to the absolute barrenness of the morainic mounds that the possibility of connecting the two groups of phenomena with the same event did not occur to me; but Dall's observation of ice remnants in the moraine in 1880 suggests a local cause for the sterility of the gravel mounds and leaves the matter in doubt.

SUMMARY OF MODERN CHANGES

During the last twenty years much attention has been given to the variations of glaciers, and a large body of facts has been collected, especially with reference to European examples. In attempts to generalize these facts serious difficulties have been encountered, and their discussion has not yet resulted in a satisfactory theory of the causes of change. All students of the subject feel the need of more extended observation, and from the point of

view of the theorist there is special interest in the history of changes in regions remote from those which have heretofore received chief attention. Comparatively little is known of the history of American glaciers, but the available data have been carefully collated by Russell[1] and Reid,[2] and an important contribution has recently been made by Klotz.[3]

The local descriptions of the preceding pages contain the additional observations made by the Harriman Expedition, together with inferences as to modern changes; but as the paragraphs on variations are somewhat scattered, the principal inferences are here assembled in résumé. The geographic order, from east to west, is retained.

In Glacier Bay the observations pertain to a large area, containing at the present time a considerable number of separate trunk glaciers. The data concerning variations are not equally full in all parts, but so far as comparable they are harmonious. It is probable that the history of the whole district centering in the bay is a unit. The history begins with an epoch when the glaciers were smaller than now. During this epoch a forest grew to maturity and then was overwhelmed by gravelly waste from the ice; the epoch was therefore measured by centuries. The glaciers then advanced many miles, attaining a maximum one hundred or one hundred and fifty years ago, and they have since retreated. Measured to the Muir Glacier, the total retreat to 1899 was more than fifteen miles; measured to the Grand Pacific, it was more than thirty-five

[1] Climatic Changes indicated by the Glaciers of North America: Am. Geol., vol. IX, pp. 322–336, 1892. Reprinted, with little change, as chapter VIII of Glaciers of North America.

[2] Variations of Glaciers: Jour. Geol., vol. III, pp. 278–288, 1895; vol. V, pp. 378–383, 1897; vol. VI, pp. 473–476, 1898; vol. VII, pp. 217–225, 1899; vol. VIII, pp. 154–159, 1900; vol. IX, pp. 250–254, 1901; vol. X, pp. 313–317, 1902.

[3] Notes on Glaciers of southeastern Alaska and adjoining territory. By Otto J. Klotz. Geog. Jour., vol. XIV, pp. 523–534, 1899.

miles. The retreat was interrupted by a temporary advance between 1890 and 1892.

La Perouse Glacier is practically at maximum now. It has not been greater for centuries, except that it was a little longer a few years ago, when it invaded a mature forest. As its neighbors at the east and west were much smaller a century ago, analogy suggests that the present maximum was preceded by an important minimum.

In Disenchantment Bay and its dependencies a great retreat, amounting to at least five miles along one channel of outlet and thirty miles along another, has been in progress for more than a hundred years. There is evidence of other changes, but their order and dates are unknown.

Columbia Glacier is practically at maximum now, and was nearly as large in 1794, but an important minimum probably occurred within the nineteenth century. It has not been greater than now for centuries, except that it was a little larger about the year 1892, when it invaded a mature forest.

The numerous glaciers of Port Wells, including College and Harriman fiords, may have a harmonious recent history, but the data are too meager to warrant a definite statement. They are somewhat smaller than at a maximum which may have occurred fifty to one hundred years ago.

Grewingk Glacier has not for centuries been much larger than now. It was somewhat larger between fifty and one hundred years ago, and may have had a subsequent maximum of nearly the same extent.

The most conspicuous fact brought out by the comparison of local histories is that they are dissimilar. Nevertheless, there are limited resemblances. The Glacier Bay and Disenchantment Bay histories agree in including a great retreat, occupying more than a century. The Port Wells and Grewingk histories agree in a moderate retreat occupying something less than a century. The La Perouse

and Columbia histories agree in a present condition of maximum glaciation probably preceded by an important minimum.

As glaciers grouped together (about Glacier Bay, Disenchantment Bay, etc.) have seemed to vary in harmony, it is natural to look for a systematic geographic arrangement of the diverse histories; but such arrangement is not apparent. Port Wells and the Grewingk Glacier, intermediate in type of variation, are the most westerly of the localities (see map, fig. 55). Between Glacier Bay and Disenchantment Bay, representing one extreme of variation, flow La Perouse Glacier and its neighbors representing the opposite extreme. La Perouse and Columbia glaciers, agreeing in phenomena of variation, are separated by the contrasted phenomena of Disenchantment Bay.

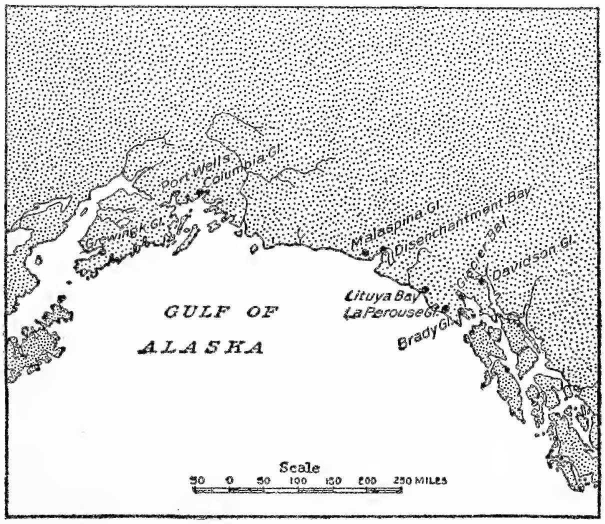


FIG. 55. DISTRIBUTION OF GLACIER LOCALITIES.

Glacier Bay adjoins Lynn Canal, being separated only by a mountain range, and some of the high névé fields of this range feed glaciers of both slopes. On both sides the glaciers are believed to be retreating, but the front of the Davidson of Lynn Canal is less than half a mile from the forest on its old moraine, and the Muir of Glacier Bay is nearly twenty miles from the equivalent forest. The great Fairweather Range, separating Glacier Bay from the Gulf

of Alaska, nourishes many glaciers. Of these the Johns Hopkins, descending northeastward, has shared the great retreat of Glacier Bay; but the Brady, flowing south, and the La Perouse and Crillon and their neighbors, flowing southwest, have advanced during the same period.

Close to Disenchantment Bay lies the Malaspina, a piedmont glacier fed by alpine glaciers of the St. Elias Range. From other slopes of the same range come the principal feeders of the Hubbard, the main glacier of Disenchantment Bay. In a century or two the Hubbard has retreated five miles up Disenchantment Bay, but the Malaspina is bordered in places by a mature forest from which it has retired only a short distance, and at one point it has even advanced against the forest within a few years.[1]

The general fact appears to be that mere proximity does not ensure parallelism of glacial history; on opposite sides of a mountain range the sequences of change may be not only different but antithetic.

THEORIES

In the discussion of the causes of the advance and retreat of European glaciers the phenomenon occasioning greatest difficulty is the lack of parallelism between the variations of different glaciers and different groups of glaciers. The histories of glaciers of the Alps exhibit disparities similar to those of Alaska, with the apparent difference that the Alaskan disparities are of larger scale, just as the Alaskan glaciation has a larger pattern; and the arctic and boreal glaciers of Europe probably exhibit equal irregularity, although Rabot, who has recently assembled the evidence, finds a number of partial correspondences.[2]

[1] I. C. Russell. Amer. Geol., vol. IX, p. 329, 1892.

[2] Les variations de longueur des glaciers dans les régions artiques et boréales. Arch. des Sci. Phys. et Nat., 4me periode, vols. 3, 7, 8, 9, Geneva, 1897–1900.

For the explanation of irregularity there are two prominent hypotheses. The first, regarding oscillation of long period as climatic, ascribes minor oscillations to the rhythmic gorging and disgorging of the névé reservoir. The rhythmic period, being connected with topographic conditions, is different in different glaciers.

The second, which has been more fully developed, appeals to the principle of lag. The chief cause of variation of the wasting end of the glacier is believed to reside in variation of snow accumulation on the névé fields, but considerable time is required for the transmission of the effect from end to end of the glacier. For average Alpine glaciers this time is believed to amount to several decades, but it varies with the length, slope, and other peculiarities of the individual ice streams, and the general result of its variation is that ice streams of the same mountain slope, or streams flowing from the same névé, initiate a period of advance or retreat in different years or even different decades.

It is impossible to compare the first hypothesis with the behavior of Alaska glaciers, on account of the meagerness of observational data. As yet we know nothing of periodicity of variation. The comparison of the second is obstructed by the lack of meteorologic records for the glacier region, and by the fact that very few of the determinations of variations are associated with definite dates; no comparison with climatic variation is possible, and the comparison of individual histories of variation, one with another, is approximate only. Nevertheless, some judgment may be formed of the general competence of the second theory; and it seems to me not fully adequate for the explanation of Alaskan disparities.

Consider, for example, the contrasted histories on opposite sides of Fairweather Range. On the northeast slope a great advance culminated not less than one hundred

years ago, and a great retreat has been in progress ever since. On the south and southwest slopes the same period of one hundred years has witnessed a general advance. The century's variation for one side of the range, in a general way and so far as known, is the reverse of the variation for the other side. To apply the principle of lag to the phenomena it is necessary to suppose that the glaciers of one slope are very far behind those of the other in some phase of variation. If the southwestern group are considered the slower to respond to variations of névé supply, the inference is that they are now at or near a culmination corresponding to the culmination of the northeastern group a century or more ago. If the northeastern group are considered the slower to respond, the inference is that though now at very low ebb, they have not yet felt the impulse which has carried the southwestern group to a maximum; and many decades, if not a full century, will be required to bring them to the same phase. It is not clear to me which horn of the dilemma should be taken, but in either case the time interval between corresponding phases is greater than can reasonably be ascribed to lag.

Associated with the theory of lag as applied to the variations of European glaciers is a generalization that glacial variation is rhythmic, with a period of about thirty-five years, each recurrent cycle of variation being brought about by a corresponding cycle of climatic change. In this respect also the Alaskan phenomena are discordant. It is not credible that the great advance and retreat which occurred in Glacier Bay, involving the extension of glaciers along the main trough for thirty-five miles, or more, and their subsequent melting, could be accomplished in so short a period as thirty-five years; for, though direct observation has covered but a small part of the great oscillation, it has shown that in the half of thirty-five years the retreat of the ice front was less than five miles.

Reid has suggested a local subsidence of the land as a possible explanation of the retreat of the glaciers of Glacier Bay.[1] Stumps of trees that grew in Muir Inlet before the great advance of the glacier, now stand at low-tide level, and demonstrate a submergence of at least twenty feet. The submergence may have been greater; and he points out that any lowering of the surrounding land with reference to the sea would make the conditions less favorable for the accumulation of snow and tend to reduce glaciers. To extend this explanation so as to cover the diversity of local histories it would be necessary to assume that the Fairweather Range was not lowered in company with the adjacent tract about Glacier Bay; and it would be logical also to assume that the great expansion of Glacier Bay ice which preceded its shrinkage was associated with a rise of the surrounding land. As there is independent ground for believing that the region is one of active mountain growth, the occurrence of such differential and diverse movements is quite conceivable, and their possibility should be kept in view in the study of each locality. But as glaciers are highly sensitive to climatic changes, as climates are subject to continual and rapid variation, and as earth movements are comparatively slow and moderate in their influence, the central theory of glacier variation is necessarily climatic rather than diastrophic.

With reference to the climatic explanation of the Alaskan phenomena I have a suggestion to contribute — a suggestion of a somewhat vague character, not yet reduced to the form of a definite hypothesis. It is, that the combination of a climatic change of a general character with local conditions of varied character, may result in local glacier variations which are not only unequal but opposite.

[1] Nat. Geog. Mag., vol. IV, p. 40, 1892.

The general drift of the suggestion may be illustrated by considering some of the more evident consequences of an assumed change in the temperature of the water of the Gulf of Alaska. Let us assume that the water becomes warmer, and that all other factors affecting glaciation remain unchanged. The consequences would include:

1. A higher temperature for the air currents flowing from the gulf to the land.

2. A greater contrast in temperature between the coastal belt and the interior of Alaska, especially in winter.

3. Greater evaporation from the ocean and a higher humidity for the landward-flowing air — resulting from 1.

4. Greater precipitation on the mountains, especially in winter — resulting from 2 and 3.

5. A shorter annual period in which precipitation takes the form of snow — resulting from 1.

6. A (probably) lower ratio of snow to rain — resulting from 5, qualified by 4.

7. A higher snow-line.

8. More rapid waste of ice and snow by evaporation and melting—resulting from 1, 5 and 7.

Of these consequences, the increase of precipitation would tend to enlarge glaciers, while the lessened ratio of snow precipitation and the enhanced wasting would tend to reduce them.

Evidently a lowering of the temperature of the gulf water would be followed by the reverse consequences.

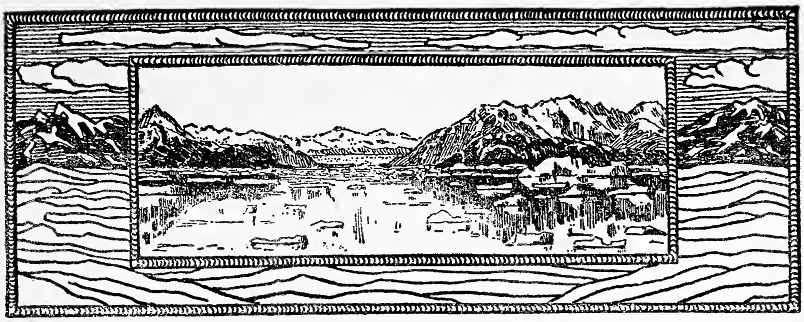
If the hypothetic rise of ocean temperature were carried to an extreme, the snow-line would be driven above the mountain tops and the glaciers would disappear. If the hypothetic fall of ocean temperature were carried to an extreme, so as to abolish the contrast between sea and land temperatures, the southern coast of Alaska would be reduced to the condition of the western coast, and glaciers would disappear from all but the highest mountains.

There is, therefore, a temperature of ocean water which is more favorable for the development of glaciers in the coastal mountains than a higher or lower temperature. But this temperature is not the same for all parts of the coastal belt; it must vary with local topographic characters. The glaciers of a low range may be more sensitive to variations of the snow-line than those of a high range. Glaciers facing the sea may be more sensitive to the variations of wastage dependent on the temperature of the incoming winds than are glaciers facing the interior. Glaciers fed from cirques, where snow is concentrated by wind and avalanche, may respond to variations of precipitation in a very different way from glaciers fed by open névé fields, where much of the annual snowfall is dissipated by dry evaporation. The laws of variation for high-grade glaciers may be quite different from those for glaciers of gentle slope. And so, when the ocean temperature approximates the value most favorable for the development of glaciers in the district as a whole, it will be too warm for the highest development of certain glaciers and glacier systems and too cool for others. And whenever such a condition obtains, a change in ocean temperature will cause some glaciers to enlarge and others to contract.

It is of course impossible that one of the meteorologic conditions determining Alaskan glaciation should vary by itself while all other conditions remain constant, and the case assumed for the sake of illustration is therefore purely ideal. It has served its purpose if it has given plausibility to the suggestion that a change in some meteorologic factor or factors may result in simultaneous modifications of glaciers which differ not only in amount but in algebraic sign.

Whatever may be the causes of the variations of glaciers, Alaska affords an inviting field for their investiga-

tion. Intermediate in accessibility between the glacial districts of Europe and Greenland, it is more comprehensive than either in variety of local circumstance. The complexity of interacting conditions may for a long time baffle attempts at analysis, but when the complexity has been resolved, the resulting theory should have wider application than one founded on simpler phenomena.



CHAPTER II

PLEISTOCENE GLACIATION

ALL geologists who have studied the region we traversed are agreed that the glaciers were much more extensive in Pleistocene time than now; but opinions differ widely as to the actual magnitude of the ancient ice fields, and also as to the extent to which they modified the topography of the country. As the nature of my journey rendered my view somewhat cursory and superficial, and as nearly all parts of my route had been covered, with better opportunity, by one or more of my predecessors, I can not expect to settle any of the vexed questions, but it still seems best to make rather full record of my observations and impressions. When an observer views a complex phenomenon his attention is naturally directed to the particular features which his previous training enables him to appreciate — he "sees what he has eyes to see"; and the difference of eyes makes the work of independently trained observers more or less complementary.

HANGING VALLEYS

Of the various classes of evidence from which the history of Pleistocene glaciation is inferred, the physiographic is most available to observers who see the land chiefly from the deck of a vessel. Ice-scoured surfaces referable to the ancient glaciers were occasionally discovered during our journey, and a few drift deposits were closely examined; but such observations served chiefly as checks on inferences from topographic form.

The general characters of the physiographic data which may be used in such studies are familiar and need not be recited here, but a special sculpture feature — the hanging valley — may need introduction to some of my readers. Its utility in the interpretation, discrimination and estimation of the work of Pleistocene glaciers has been little appreciated until quite recently,[1] but in the study of the Alaska field it was found extremely useful.

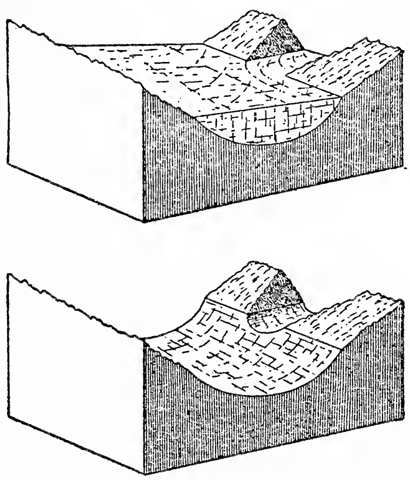
A hanging valley is a small U-valley tributary to a larger valley, the floor of the smaller being considerably higher at the junction than the floor of the larger. Many of them are short, high-grade troughs, heading in cirques; some are mere cirques, without troughs — spoon-bowl hollows, high on the walls of main valleys. They are associated with other evidences of glacial sculpture, and the elevation of their floors is believed to result, as a rule,

[1] Lake Chelan, by Henry Gannett: Nat. Geog. Mag., vol. IX, pp. 417–428, 1897. Glacial erosion in the valley of the Ticino, by W. M. Davis: Appalachia, vol. IX, pp. 136–156, 1900. Glacial erosion in France, Switzerland and Norway, by W. M. Davis: Proc. Boston Soc. Nat. Hist., vol. XXIX, pp. 273–322, 1900. Review of the last by T. C. Chamberlin: Jour. Geol., vol. VIII, pp. 568–573, 1900.

Davis's second paper reviews the literature, points out that McGee, De Lapparent and Richter had advanced somewhat similar ideas as to the origin of hanging valleys before the appearance of Gannett's paper, and mentions an unpublished address by Penck. The glacial explanation of the hanging valleys of the Alps is opposed by Bonney and Garwood in Quart. Jour. Geol. Soc. London, vol. LVIII, pp. 690–718, 1902.

from the unequal erosion of valleys by glaciers of unequal size.

Where a trunk glacier of alpine type receives a relatively small lateral tributary the main ice stream gives base-level to the tributary. Their relation in this respect is homologous with the relation of main and tributary streams of water. If the magnitude of trunk and tributary have remained constant long enough for erosion to bring about an adjustment of grades, the surface of the tributary at the point of junction has the same level as the adjacent surface of the trunk. But the bottoms of the two channels do not have the same level. The trunk stream is normally deeper than the tributary, and at their junction its bottom lies at a lower level. If the streams (of ice or water) be removed, the bottom of the tributary channel is found to end high up on the side of the main channel.



FIGS. 56 AND 57. DIAGRAMS ILLUSTRATING ORIGIN OF HANGING VALLEYS.

56. A terrestrial block containing a trunk glacier and tributary with well adjusted channels.

57. The same block without the ice, showing the adjusted glacier channels. The trunk channel is deeper than the tributary; the tributary channel is a hanging valley on the side of the trunk channel.

The ideal case, diagrammatically illustrated in figures 56 and 57, is also illustrated in the actual topography of many regions sculptured by Pleistocene glaciers.

The hanging valley is especially significant in two lines of physiographic interpretation. It is a conspicuous earmark of the former presence of glaciers; and it helps to a conception of the magnitude of Pleistocene glacial erosion.

Its value as an earmark depends on the principle of exclusion; glaciation is the only physiographic process known to produce such forms. It is true that discordance of level between trunk and tributary valleys is not by itself diagnostic of glaciation, for it often occurs as a temporary condition in systems of stream-made valleys, especially when fresh uplift stimulates down-cutting by trunk streams; but in such cases discordance is associated with the narrow trenches of youthful or rejuvenated topography. It is true also that the glacial U-trough is sometimes (though rarely) simulated by products of stream erosion, and that a hollow closely resembling the glacial cirque is occasionally produced by aqueous process; but these imitative forms belong to the middle life of a stream, when down-cutting has so slackened as to permit valleys to broaden, and they imply a harmonious grading of stream beds, inconsistent with discordance of level at the junction of tributary and trunk. But the combination of discordance of level with U-shaped cross-profiles constitutes a physiographic type peculiar to the work of glaciers.

The significance of the hanging valley for the valuation of glacial erosion depends largely on the assumption that the discordance of level was produced by the glacial excavation of the main trough, and this assumption requires qualification. If *ABC* in the diagram (fig. 58) be the cross-profile of a main glacial trough, *DE* the longitudinal profile of a tributary trough, and *EF* the produced floor of the tributary, the 'discordance' is represented by the height of *F* above *B*. If the preglacial stream valleys were accordant in grade, their junction was at *F*, or some point above *F*; and *FB* is the measure either of the deepening of the main trough by the

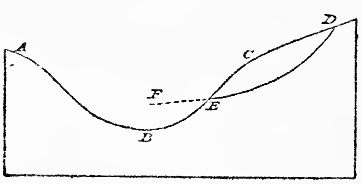


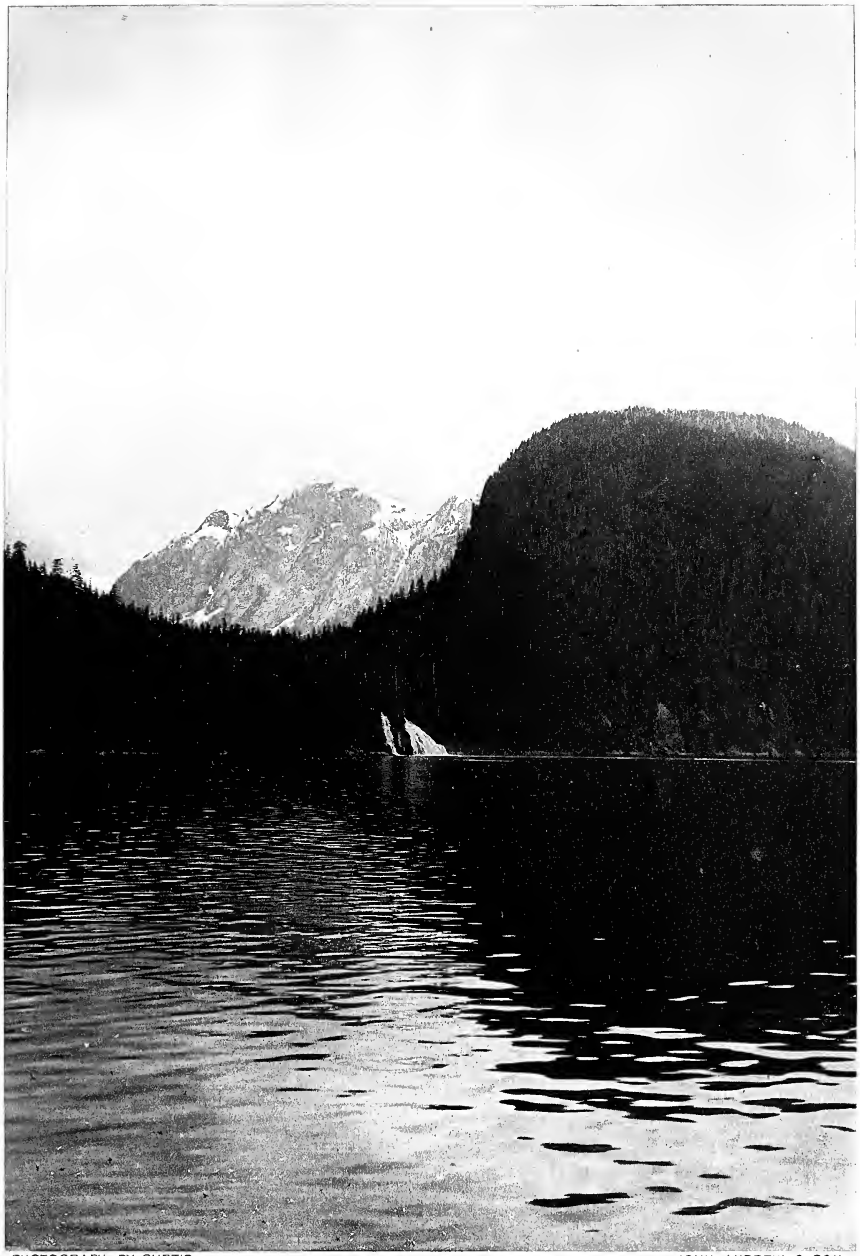
FIG. 58. DIAGRAM ILLUSTRATING DISCORDANCE OF HANGING VALLEYS.

EXPLANATION OF PLATE XVI

A Hanging Valley, Fraser Reach

Fraser Reach is a long, deep channel, or fiord, of the 'Inside Passage,' here about two miles wide. The hanging valley is in Princess Royal Island, and joins the fiord trough from the southwest. Its sill is several hundred feet above the water surface.

From a photograph made by E. S. Curtis, June 3, 1899. Negative no. 187.



PHOTOGRAPH BY CURTIS JOHN ANDREW & SON

A "Hanging Valley," Fraser Reach.

glacier, or of the difference between that deepening and the deepening of the tributary. If the preglacial valleys were discordant, the main valley must have been young, and was probably so narrow that its conversion into a U-trough involved much excavation at the sides. In either case, therefore, the occurrence of high hanging valleys is indicative of great erosion by ice.

Yet another qualification is necessary, for there is a special condition under which a relatively young stream valley may have the width of a glacial U-valley. When the activity of streams is revived by uplift, the general degradation may be outstripped not only by trunk streams but by strike streams following outcrops of weak rocks; and if the contrasts of rock resistance are great, a broad belt of weak rock may induce the development of an open valley or wide trough, while neighboring uplands of resistant rock are still little modified. Thus may arise a topographic condition susceptible of conversion by only a moderate amount of subsequent ice work into a typical glacier trough with hanging valleys.

Theoretically, then, there are at least three cases to be borne in mind in inferring the quantity of glacial erosion from the existence of hanging valleys. First, the grades of preglacial streams may have been accordant, in which case the discordance of hanging valleys with trunk valleys yields a rough measure of the depth and amount of glacial erosion. Second, the grades of preglacial streams may have been discordant, and without dominant control of contrasted rock texture, in which case the erosive work of ice may have consisted chiefly in the enlargement of V-gorges to U-troughs. Third, the discordance of preglacial grades may have been associated with the rapid opening of valleys in weak rocks, in which case the erosive work of ice may have been small. The criteria for discriminating the three cases have not been worked out,

but a few general propositions may be advanced. In the first case a study of the district should discover independent evidence of the maturity of the preglacial topography. In the second and third there should be independent evidence of rejuvenation of preglacial streams. The third could not arise unless the main troughs follow the strike.

The practical problem is further complicated by the fact that the type of initial topography, when determined, leads to only a limiting value for the total erosion, and also by the complexity of glacial history as dependent on climatic variation. A glacier which begins erosive work by broadening and rounding the cross-profile of a stream gorge does not cease activity when that result is attained. One which falls heir to a weak-rock strike valley, fairly adjusted to its conditions of flow, may carry the work of excavation far beyond the grade limit of the ancestral stream, and hollow out a lake basin or fiord trough. And the coordinated system of grades and channel forms toward which the erosive work of grouped glaciers tends, is itself modified by every change of the general volume of ice.

But despite all qualifications the hanging valley is the most important witness yet discovered to the magnitude of the work accomplished by the alpine glaciers of the Pleistocene.

The hanging valleys of Alaska are illustrated by many of the figures and plates of this volume. The mouth of one overlooking Hidden Glacier is imperfectly shown in plate v and figure 28, and an alpine valley truncated below by erosive action of the glacier appears in plate vi. Figure 30 shows the mouth of a hanging valley above Nunatak Fiord; a glacier issuing from a hanging valley north of Nunatak Glacier is shown in figure 31; and a glacier cascading from a hanging valley of the south side of the same trough in figure 32. Figure 43 shows a tributary to Yale Glacier issuing from a hanging valley, and figures 44

and 45 a series of similar valleys and glaciers bordering College Fiord and Harvard Glacier. In figure 46 two hanging valleys are shown, the one empty, the other furnishing a tributary to Barry Glacier; in figure 50 are two high valleys with small glaciers overhanging Serpentine Glacier; and figure 51 represents Cataract Glacier, issuing from a high valley and cascading to Harriman Fiord. All these examples, occurring in the preceding portion of this report, are incidentally included in views selected to illustrate other features. In the following portion are a number of views chosen wholly or partly with reference to hanging valleys; and the remark applies especially to plate XVI and to figures 62, 66, 69, 70, 71, 72, 74, 76, 77, 81, 88 and 93.

THE DISTRICT OF INLAND PASSAGES

From Puget Sound, Washington, at the south, to Lynn Canal and Glacier Bay, Alaska, at the north, a space of 900 miles, the coast of North America has a peculiar and significant facies. It is divided into a fringe of rugged peninsulas by deep, narrow inlets, and guarded from the surges of the open ocean by a great number of rocky islands and islets. In this respect it resembles the coast of Maine and the western coast of the Scandinavian peninsula, and, like them, its peculiar characters are associated with evidences of extensive glaciation. It differs from those coasts in the fact that some of its islands are of great extent, so as to include or be constituted by mountain ranges, and in this respect it is paralleled by a single district only, the western coast of the southern extremity of South America.

The map of the district, figure 59, though drawn to so small a scale as to show only the larger islands and principal fiords, serves to illustrate the intricate penetration of the land by the sea. It is reduced from the large chart (3689) of the U. S. Coast Survey.

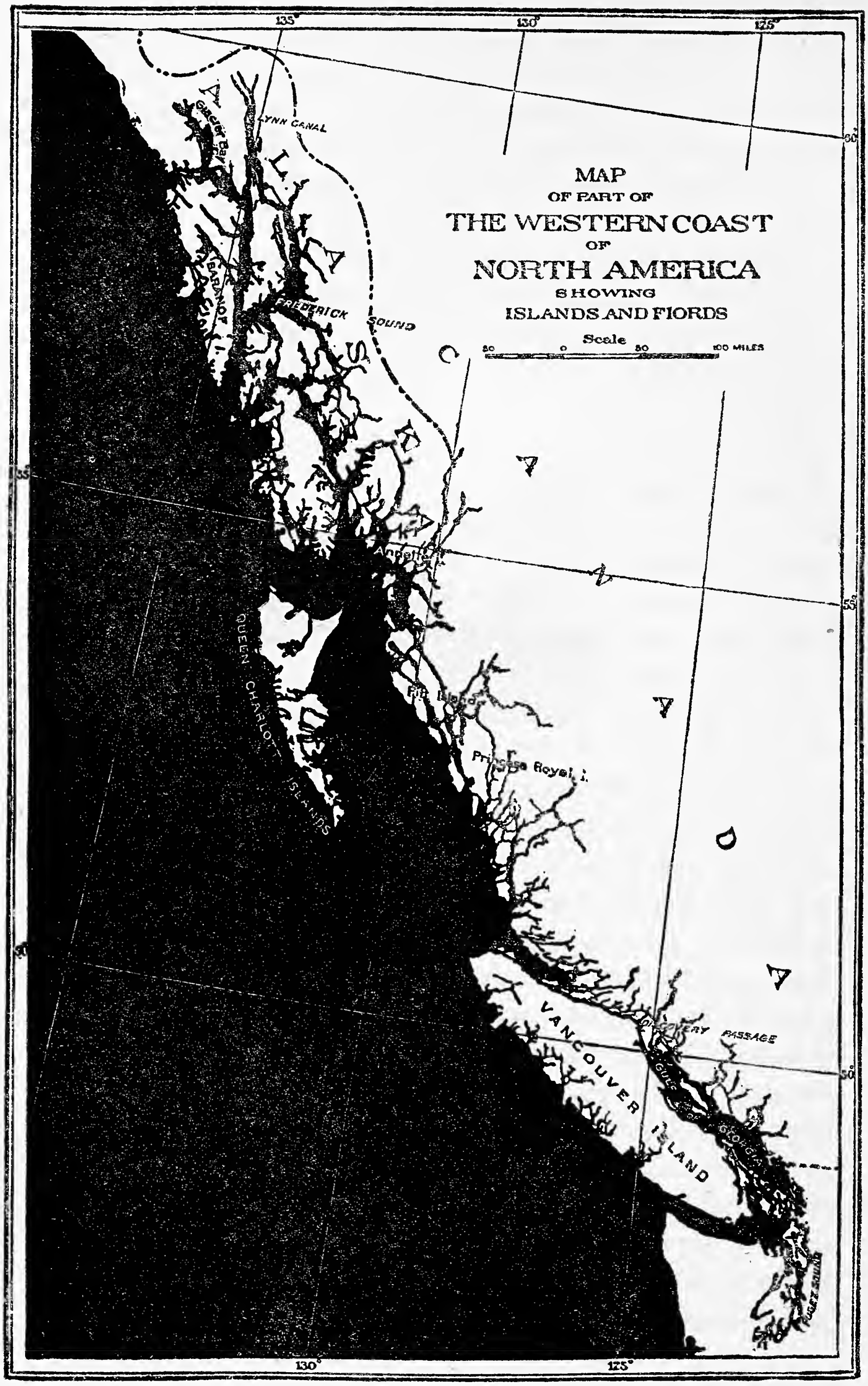


FIG. 59. FIORDS OF THE INLAND PASSAGE DISTRICT.

The general trend of the coast of the mainland is northwest to north-northwest, and this trend is shared by the longer axes of the principal islands. There are thirty-two islands exceeding twenty miles in their greater dimensions, the maps show more than 400 islands above one mile in extent, and the islets are uncounted.

With minor exception, the peninsulas and islands are mountainous, descending steeply to the water, and the passages between them are deep. Most of the inlets of the mainland and many of the passages dividing islands are of approximately uniform width for long distances, and the parallel shores of such linear waterways are usually steep and somewhat simple in contour. Repeating thus the characteristic features of the Norwegian coast, they fall within the physiographic class to which the name fiord is applied. The northwesterly trend characteristic of the islands affects also the passages between them, and has enabled navigation to select for its use a route close to the mainland, where deep waters are almost wholly protected by the islands from waves and storms of the open ocean. This route is commonly known as the 'inside passage.' Our steamer followed it on both the outward and return voyages, our principal deviation from it being made by a visit to Sitka, which lies on the southwest or oceanic side of Baranof, one of the outer line of islands. Parts of the journey were made at night, but the outward and inward courses, taken together, showed us much the

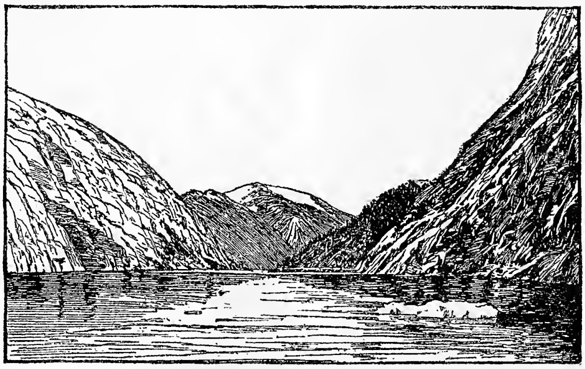


FIG. 60. AN ALASKA FIORD; TRACY ARM, HOLKHAM BAY.

greater part of the inside passage, and our examinations about Sitka occupied several days. An excursion to White Pass gave a view of a canyon at the head of a fiord, and of uplands at 2,000 to 2,500 feet altitude, but the higher summits were seen only from stations at or near sea-level.

Direct observation of the uplands was afterward supplemented by the study of photographs. The U. S. Coast and Geodetic Survey and the Canadian International Boundary Commission have used the camera freely in connection with topographic surveying, and I was so fortunate as to have access to their series of pictures. The latter organization spread a web of triangulation over all the mainland portion of southeastern Alaska, and from each of the mountain peaks occupied as stations photographed the entire horizon, using the views afterward for the construction of contour maps. Their album thus represents the upland in a systematic and thorough way and is eminently adapted to physiographic study. (See page 6.)

In this, as in other districts of Pleistocene glaciation, it is evident that the Pleistocene sculpture is superposed on an earlier sculpture, chiefly aqueous; and in the discussion of the work of Pleistocene glaciers it is necessary to consider the pre-Pleistocene condition. I find it convenient to begin with that consideration.

Pre-Pleistocene Topography

So far as we saw the indurated rocks, and so far as we know them from the descriptions of others, they are either igneous or metamorphic. The igneous rocks are almost wholly intrusive. The metamorphic exhibit various degrees of alteration, but all are so folded or squeezed that the planes of structure make large angles with the horizon. The general strike is believed to be parallel to the coast, but there are few direct observations of strike. In-

ference rests partly on the trends of structure lines determined by the Canadian Geological Survey in neighboring parts of the continent, partly on the trends of the straighter valleys and channels of the region itself.

From this complex the pre-Pleistocene topography was developed by erosion. The only constructional forms we saw which might have antedated the Ice Age were a few volcanic cones. The system of relief was related to three known base-levels. The plane of the first is now high in air, above some of the mountains and among the peaks of others. The second is not far from present sea-level, and the third is below sea-level.

The High Peneplain. — The uplands of the mainland are remarkably uniform in general height over large areas, not indeed presenting plain surfaces, but either exhibiting harmony of crest lines, despite profound and general dissection, or else occupied by numerous small shallow valleys, which are strongly contrasted with the deep steep-walled trenches of a less complete dissection. These features can be most readily presented in connection with some of the accompanying illustrations. Figures 3, 61, 62, 63, 75, and 77 were drawn from photographs by the Canadian Boundary Commission.

Figure 61 shows the upland topography north of the western end of Cross Sound. (The reader can identify the locality on the map, page 120, as the third cape west of the mouth of Glacier Bay.) We stand on a summit above Cape Spencer, and look northwest. At the left is the Pacific Ocean; in the center distance, the end of Fairweather Range (the nearest high peak being La Perouse, 10,750 feet); at the right, Brady Glacier, its foot separated from Taylor Bay by a gravel strand. Between us and the base of the mountains, 18 miles away, are a series of hills somewhat uniform in height. The higher points (as we learn from the Commission's contour map)

range from 2,000 to 2,500 feet above tide, and near the mountain rise above 3,000 feet.

Viewing these hills collectively, one can hardly fail to be impressed with the appearance of system in their crest lines. Some of the hills have broad and flattish, or gently arched, backs; and all the higher parts of their profiles seem to belong to a single gently sloping plane. Should the valleys between them be filled up even with the crest lines, the group would become a plateau with undulating surface. It is natural for the geologist, when he sees such a harmonious arrangement of hill tops, to seek an explanation in the structure of the rocks, but in this case a structural explanation can not be found. The rock layers are not horizontal but nearly vertical, and they have been cut across in the shaping of the land. The local elements of the upland forms are due purely to erosion. The most probable explanation of the phenomena is that the area was first worn down to a plain at or near sea-level, afterward raised so as to be a plateau, and then dissected into a group of hills. The habit of the hills indicates that the principal work of dissection was by streams, but there was also glacial sculpture. They were overrun by the ice-sheet, and the glacial rounding of summit angles helped to obscure, though it failed to destroy, the evidence of the old base-level plain.

Yet other evidence of the geologic history is connected with the trends. The rock structure strikes northwest, or from the foreground toward the mountains, and this is also the trend of the upland as a whole. But the crests of individual hills trend east of north, making angles of 50° to 60° with the strike; and the separating valleys have the same trend. The valleys do not head against high summits among the hills, but traverse the plateau from side to side. They seem to be the work of a system of streams whose courses across the plateau were deter-

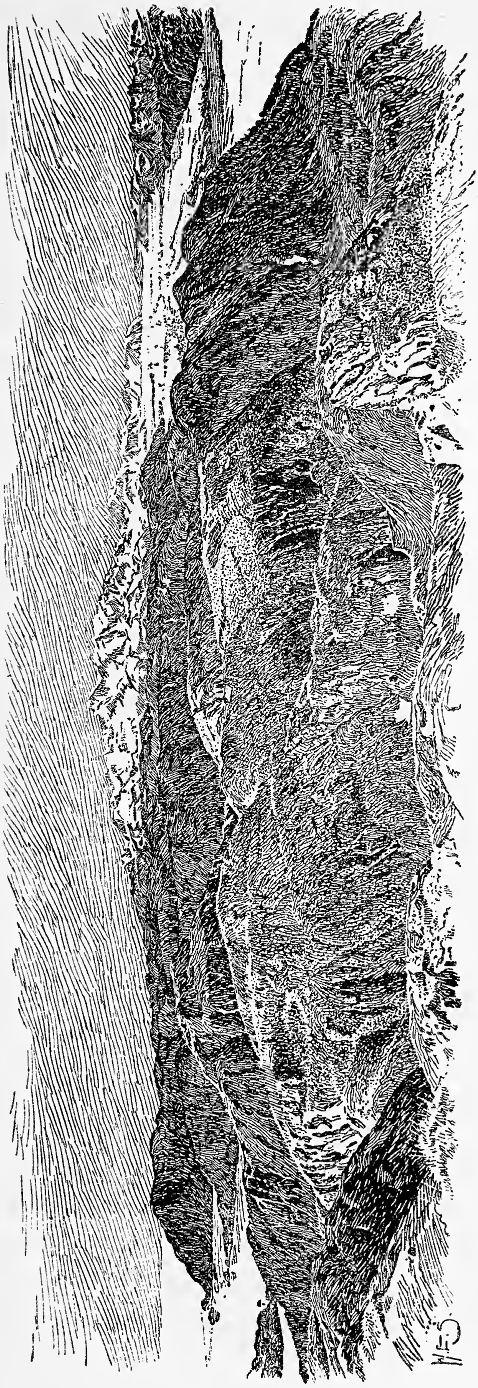


FIG. 61. UPLAND TOPOGRAPHY NEAR CAPE SPENCER.
A chain of hills carved from an original plateau. See page 123.

mined by some cause other than the rock structure. As their direction coincides with that of the local inclination of the old peneplain, it is highly probable that they were superposed on the rock structure at the time of the uplifting of the plateau. The great valley holding Brady Glacier and Taylor Bay, on the other hand, runs parallel to the strike of rocks exposed in the hills, and may fairly be assumed to occupy the outcrop of a belt of comparatively weak rocks.

If now we project the summit plane of the

hills backward across the Brady-Taylor valley, we find that it passes among the highest peaks of another and higher upland, an upland lacking the broad summits of the Cape Spencer hills, but characterized instead by notable uniformity in the height of numerous acute summits. A suggestion of this character may be seen at the right in figure 61.

Before leaving this view, note should be made of the fact that the peneplain of the Cape Spencer hills ends northward at the base of Fairweather Range. The range is distinct in physiographic type and in geologic history.

The reader is now asked to turn back to figure 3, drawn to give a bird's-eye view of Davidson Glacier, but showing also the east wall of Lynn Canal. The point of view is not quite so high as the crest of the opposite wall, but is high enough to show that the upland bounded by that wall has plateau characters. There are none of the smooth crest lines seen in figure 61, but angular peaks and crests standing close to the mural face combine with angular peaks and crests farther back to give an even sky-line. All the valleys visible are upland valleys, and it is not hard to believe that these have been carved out of an uplifted block, the plane of whose original flat top runs among or above the phalanx of sharp summits.

This upland stands about 3,000 feet higher than the hills of Cape Spencer, and is eighty miles northeast of them. The intervening uplands are parted by two great fiords, Lynn Canal and Glacier Bay, and are considerably dissected in detail, but where most massive they have the plateau habit shown in figure 3; and they are intermediate in height between the plateaus at east and west.

In figure 62 we have the view commanded from a peak like one of those against the sky in figure 3. The locality is twenty-five miles farther south, and we are looking eastward from a point about five miles east of Lynn Canal.

The higher summits have a general altitude of 5,200 feet. It is now evident that the sculpture is that characteristic of the work of local glaciers. The sharp peaks overlook cirques, many of them still filled with ice; below the cirques are short glacier troughs; and between the troughs are narrow crests. These glacier troughs are not insignificant features—the beds of those in the field of view lie 1,000 to 2,500 feet below the plane of the high peaks—but they are so small in comparison with the great earth block from which they have been hewn that they do not prevent the imagination from restoring its original outlines.

FIG. 62. UPLAND TOPOGRAPHY NEAR BERNER BAY.

A deep long glacier trough traverses the view from distance to foreground. It is occupied in part by a glacier, in part by a filling of glacial waste; and its rock bed is far below sea-level. It is related to the fiords and must be considered in another connection. In the present connection it need be thought of only as a trench dividing the upland, and helping, through contrast, to exhibit the upland's plateau character.

Other illustrations of the plateau dissected by Lynn Canal and its branches are to be seen in figures 75 and

77. In each case the point of view is so low that the upland peaks do not unite in an even sky-line, but other plateau features are brought out.

The correlation of the Cape Spencer peneplain with the Lynn Canal plateaus brings together very different topographic types, but they are not essentially incongruous. The greater height of the inland district has caused it to be occupied by local glaciers, which have scooped out a system of cirques and rounded valleys, leaving the intervening crests angular. The cape district is and has been too low to initiate glaciers, but has been overflowed by

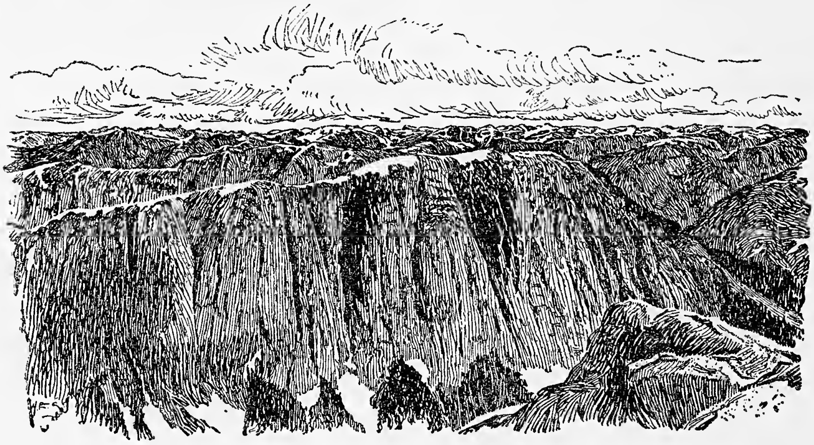


FIG. 63. UPLAND TOPOGRAPHY NEAR WALKER BAY, BEHM CANAL.

an ice-sheet originating outside it. It therefore lacks cirques and the sharp crests developed by cirque erosion, but has suffered a somewhat equable reduction of its flattish summits.

In turning attention now to figure 63, we leave the region of Lynn Canal and pass three hundred miles southward to the Walker Bay region near Behm Canal. The general height of crests is here 4,000 feet. The even skyline includes a few sharp peaks, suggesting the cirque sculpture of the northern area, but most of the distant summits and all of the nearer are rounded, as by an over-

riding ice-sheet. The deep dissection indicates a subsequent history different from that at the north, but the evidence of an initial peneplain is at least equally clear. The approximation of the summit heights to uniformity is too close to be accounted for without the hypothesis of an uplifted plain; but the departures from uniformity indicate that little if any of the original plain survives.

The general interpretation of these upland features appears to be as follows: After the folding and squeezing of the metamorphic rocks, there was a long period of erosion, in which broad tracts of the land were worn down nearly to sea-level. Then came uplift, producing a plateau from 3,000 to 6,000 feet high, and erosion has followed. In some places, at least, this plateau sloped gently toward the sea, and its plane may have remained everywhere continuous, diversified only by moderate flexures; but there is also possibility that it was interrupted here and there by faults. The period of subsequent erosion has been long enough for the development of local peneplains at a lower level, and in that time the plateau has been greatly modified. Not only has it been dissected by the eating out of gorges and valleys, but its back has been worn and fretted, largely by local glaciers, until all the original surface and much of the original form have disappeared. What remains is chiefly a tendency to uniformity of crest height in the ridges and peaks of certain districts.

It is probably true also that vestiges of the high peneplain are conspicuous only where the rocks are comparatively durable. Our best examples are along the mainland east of the archipelago, and that region, according to Dawson, is largely granitic. The dominant rocks of the archipelago are metamorphic, and we saw little from the ship's deck to suggest that the uplands of the islands have a plateau habit. The mountains next the

water do not in general rise very nearly to the plateau plane, and we were frequently able to see that those farther back are higher. Even where the channels between islands are most sharply incised it is probable that they are excavated in the bottoms of broader hollows.

My general conception of the configuration at the date of the lower peneplain — a conception necessarily vague, as well as provisional — is that it included all phases of the topographic cycle, being infantile to adolescent where the rocks are most resistant, adolescent to mature in the greater part of the Alexander Archipelago, and senile where the rocks are weakest. In the granites were narrow gorges, set far apart, and reduced to low grade only where draining large tracts. Between them were tabular uplands with mild relief, except for occasional unreduced peaks, or monadnocks. In the stronger metamorphics a system of graded waterways divided the upland into mountain ridges, with scattered remnants of the summit plain. The master streams were largely consequent to the seaward slope of the old plain, but were in part diverted to lines of strike; and minor streams were adjusted to rock structure.

Low Peneplains.—Along the passages and channels we traversed, bold coasts are the rule and forelands of any character the rare exception, but at two localities we saw unmistakable traces of a peneplain between mountain base and the descent to deep water, and in the light of their evidence it seemed proper to give a similar interpretation to various features of obscurer character.

Annette and Gravina islands lie next to the mainland in the southern part of the Alexander Archipelago. Outside them on the west is the great Prince of Wales Island, from which they are separated by a broad channel, 1,500 to 1,700 feet deep. Each island contains a mountain mass bordered on the west by a low foreland, the foreland being

related to the mountain as peneplain to monadnock. On Annette Island, where we landed, the foreland is not continuous, being divided by a bay, but its parts, together with several low islands, appear to be remnants of a more extensive plain. The rock is slate and mica schist, and that of the adjacent portion of the mountain quartzite. In detail the surface is somewhat uneven, low moutonnée bosses alternating with hollows that hold pools and bogs, but there is a general and gradual ascent from the sea front to the mountain base, where the altitude may be three or four hundred feet. Figure 64 presents one rem-

FIG. 64. PART OF ANNETTE ISLAND.

Showing relation of foreland (peneplain) to mountain, as seen from New Metlakatla.

nant of foreland in profile, as seen from the other, and includes also rocky islets.

As this whole region was deeply buried by Pleistocene ice, the unevenness of the foreland is readily understood as the result of glacial erosion subsequent to the original planation. Probably none of the original surface remains, but the glacial degradation must have been locally quite moderate, or the general plain character would not have survived. The phenomena do not yield a close determination of the pre-glacial relation of sea-level to land, but it could not have differed greatly from the present.

The second locality is Sitka Sound, 175 miles to the northwest, and on the ocean front of the archipelago. Back of Sitka the mountains of Baranof Island rise abruptly to a height of several thousand feet, and they are penetrated by inlets and lake valleys exhibiting a moderate development of fiord characters. But the town

itself stands on a foreland carved from the rock, and this foreland slopes gradually under the water of the sound or bay. In detail the foreland is even more rugged than that of Annette Island, and where it passes beneath the water its eminences give rise to a great number of islets, which stud the sound and form the natural breakwater of Sitka Harbor. The relations of mountain, foreland and islands are well shown in plate XVII (lower view) and figure 65, which represent Cape Baranof, a few miles south of Sitka. Here also the indicated base-level has approximately the height of modern sea-level.

FIG. 65. OLD PENEPLAIN NEAR SITKA.
Seen from the timber line on Mount Verstovia.

About Wrangell and Wrangell Strait, a region on the landward side of the archipelago, we saw more extensive tracts which probably pertain to the same base-level. They stand somewhat higher, averaging several hundred feet in altitude; and the parts we saw best have been so modified by glacial erosion that original base-leveling might not have been inferred without the aid of the Annette and Sitka examples. They are illustrated by the upper view in plate XVII.

Near the south end of Lynn Canal, Douglas Island is separated from the mainland by a narrow fiord, the Gastineau Channel. Facing the channel, the island is flanked by the ruins of a high rock terrace (fig. 66). A dozen short valleys of the island join the fiord at the level of the terrace, which descends southeastward from an estimated

EXPLANATION OF PLATE XVII

Upper Figure. — Lowlands near Wrangell

Standing south of the main town the observer looks southwestward across the harbor. The narrow foreland on which the town stands, and the peninsula beyond the harbor, are composed of metamorphic rocks, and are probably remnants of a dissected and greatly worn peneplain. The rounded crests of the mountains beyond suggest that they were overridden by the Pleistocene ice-sheet. See page 132.

From a photograph made by E. S. Curtis, June 5, 1899. Negative no. 195.

Lower Figure. — Foreland and Islands near Sitka

The view looks south and southwest from the hillside back of Sitka. The islands of the harbor, and the foreland beyond, Cape Baranof, are believed to be parts of a peneplain subsequently worn by a glacier. See page 131, and compare figure 65, which gives a bird's-eye view of the same features.

From a photograph made by E. S. Curtis, June 16, 1899. Negative no. 236.

PHOTO. BY CURTIS

ELSON-BOSTON

LOWLANDS NEAR FORT WRANGELL

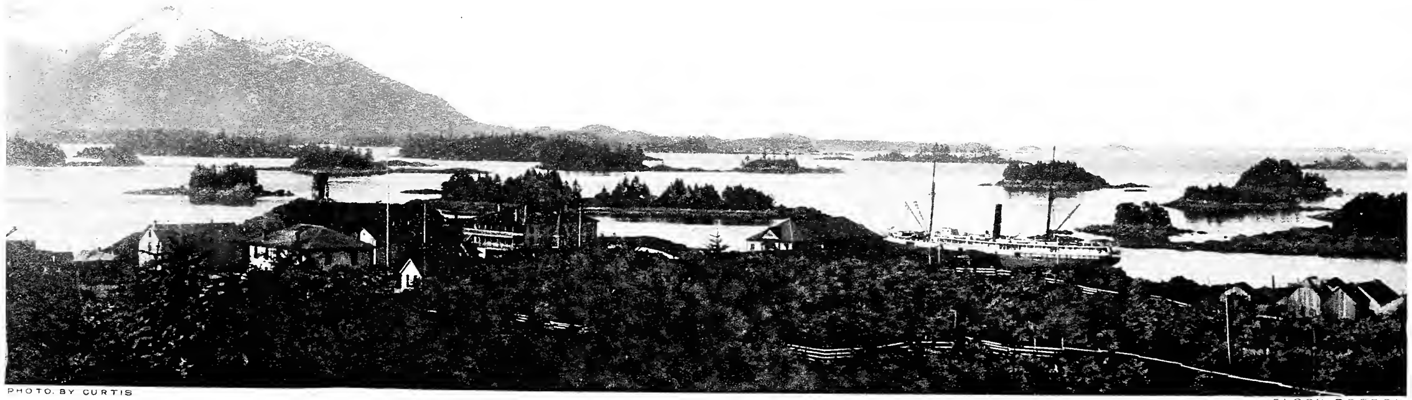


PHOTO. BY CURTIS

ELSON-BOSTON

FORELAND AND ISLANDS NEAR SITKA

altitude of 1,000 feet to 500 feet or less. The relation of this terrace to the drainage suggests that it is a remnant of a pre-glacial valley floor, and if so it may be a grade plain contemporary with the low peneplains.

These features point to a long continuance of base-level at approximately its present height, the time being subsequent to the uplift of the older peneplain. It was probably during this

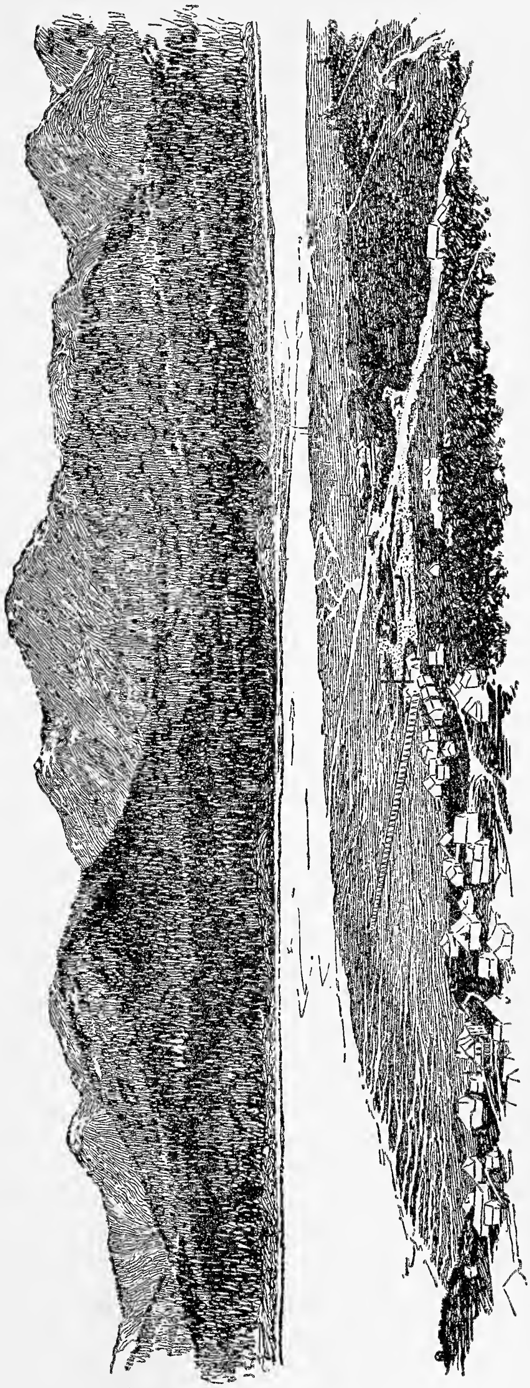


FIG. 66. DOUGLAS ISLAND, FROM JUNEAU.

The observer looks southwest across the Silver Creek delta and Gastineau Channel. The valleys of the island open along an irregular terrace several hundred feet above the water. The summits are rounded by glacial erosion.

period that the chief pre-glacial erosion of the plateau was accomplished. While the granite tables were being dissected and the harder metamorphics worn into varied and rugged mountains, flat valleys and plains were developed from the broader bodies of weak rocks.

A Lower Base-level. — The degradation of the troughs in which lie the channels, passages and straits among the islands, and the fiords of the mainland, has been carried far below the horizon of the lower peneplains. Close to the Annette Island peneplain Clarence Strait has a depth of 1,675 feet, and 50 miles farther north, where the strait is narrowed by Cleveland Peninsula, a depth of 2,100 feet is recorded. Thirty miles inland from Annette Island Behm Canal is 1,800 feet deep; and 60 miles inland, toward the head of Portland Canal, is a depth of 1,250 feet. The greatest recorded depth of Chatham Strait, 60 miles from either end and 25 miles inland from the Sitka peneplain, is 2,900 feet; and its northward prolongation, Lynn Canal, has one sounding of 2,475 feet. These figures are selected from charted soundings which indicate great irregularity of bottom configuration; they are maxima, and not averages; but the averages also are impressive. In the main part of Lynn Canal (55 miles long) the average sounding along the line of greatest depth is 1,300 feet. The similar average for the surveyed part (60 miles) of Chatham Strait is 2,000 feet; for Stevens Passage 1,000 feet, Frederick Sound 900 feet, Summer Strait 1,100 feet, Clarence Strait 1,500 feet, Behm Canal 1,400 feet, Portland Canal 1,000 feet. These are all in the region of the Alexander Archipelago. The broad sound east of Queen Charlotte Islands, called Hecate Strait, ranges from 150 to 600 feet, and the narrow passages east of it are somewhat deeper. Queen Charlotte Sound, northeast of Vancouver Island, has a general depth of 600 feet and a maximum of 1,140; the Gulf of Georgia a

rough average of 900 feet and a maximum of 1,470; the narrow passage joining the sound and gulf an average of 600 feet, with a greatest depth of 1,000. At the extreme south Puget Sound has an average depth of 500 feet and a maximum of 925.

With the possible exception of Hecate Strait, these water-filled valleys are clearly products of erosion; and it is probable, though not proved, that they are younger than the low peneplains. Whatever the extent to which they were hollowed out by rivers, they were afterward greatly modified by glaciers; and the glaciers are responsible for the conspicuous unevenness of their floors. The demonstration of ice work is found in the thorough glaciation of all bordering lands, to be presently described, and in the sculpture of rocky islets, which have characteristic moutonnée forms. Much of the unevenness, and especially the deeper basins, must be ascribed to glacial erosion, but a share may also be referred to glacial deposition.

Whatever the extent to which the hollows were deepened and enlarged by glaciers, it is probable not only that they were initiated by rivers, but that some of the rivers sunk their beds considerably below present tide-level. The most satisfactory evidence on this point was found at the extreme south. In the Puget Sound region, as shown by Willis, the ice movement was southward, a lobe of the ice-sheet ascending the broad valley of western Washington. This lobe made extensive modification of the face of the country, but chiefly by deposition and only secondarily by erosion. The system of troughs it left behind are regarded as preexistent stream valleys, only moderately scoured and straightened by the ice which overran and occupied them.[1]

[1] Drift Phenomena of Puget Sound. By Bailey Willis. Bull. Geol. Soc. Amer., vol. IX, pp. 111–162, 1898.

This interpretation by Willis seems to me reasonable. The glacial deposits in the southern part of the Puget Sound region are voluminous, and much of their material is of distant origin. This is the place where the ice lobe discharged its load, and it is not probable that in the field of deposition the ice also developed by erosion a system of narrow deep troughs. Regarded as stream valleys, the channels of the sound tell of a pre-glacial base-level at least 500 feet, and probably 1,000 feet or more, below the present sea surface.

A few features seen at the north might be regarded as confirmatory, but their interpretation is subject to considerable doubt. They are apparent exceptions to the general rule that at all low levels the sculpture forms of trough walls are glacial.

But while the existence of a pre-glacial low base-level is on the whole probable, its precise relation to present base-level and the period of its duration are altogether conjectural. To bring all parts of the deep channels within reach of stream erosion it would need to be 3,000 feet below present sea-level in the region of the Alexander Archipelago. Under present climatic conditions, such a change would carry a very large area above snow-line, and would so promote the alimentation of glaciers as to flood the whole district with ice and abolish stream erosion. Stream erosion, therefore, could not have been carried, by lowering of base-level, to the lowest parts of the channel system without the aid of important climatic variation. Without doubting the possibility of wide range in independent climatic factors, it seems easier to assume that the lowering of base-level was comparatively moderate, and that a considerable part of the down-cutting of the channels was accomplished by Pleistocene glaciers.

There is equal doubt as to the duration of the low base-level, or the extent of the erosive work it enabled

the streams to accomplish. The questions whether the broader channels of the archipelago were merely outlined by river gorges or were widely opened, whether the low peneplain was only trenched or was largely replaced by a peneplain at a level now submerged, whether the grading of river beds was restricted to the coastal district or was carried far into the interior, are not answered by any facts in my possession.

To escape the confusion arising from the glacial remodeling of water-wrought topography, it is natural to turn to the region just outside the glacial district. This region may be assumed to have shared the same oscillations of base-level, so that whatever history may be derived from it can be transferred to at least the neighboring parts of the glacial district. The glaciation of what may be called the inner coast has its southern limit in Puget Sound. As the Olympic Mountains, separating the sound from the outer coast, contained Pleistocene glaciers, the outer coast also may have been modified by ice in that latitude. But farther south the coast was not directly affected by glacial ice. Between the Olympics and the mouth of Columbia River are two shallow bays, partitioned from the ocean by sand spits. The more northerly, Gray Harbor, receives the Chehalis River, a stream of moderate size, but the map gives no indication of a delta. Willapa Bay receives two small streams, Willapa and Nasal rivers, and these also are without deltas. It is evident that the bays are estuaries, or submerged portions of the river valleys, and they indicate a recent change in the relation of sea and land, the sea rising or the land sinking.

Columbia River also ends in an estuary, its banks gradually separating, until near the sea they are ten miles apart. The estuary is shoal, and it is a matter of observation that the parts protected from the current are being rapidly filled by the abundant silt of the river. The banks

are in part low, but include also hills and bluffs. While this estuary is much larger than those of Chehalis and Willapa rivers, it is small in relation to the Columbia River, which carries a great volume of water, and the valley whose submergence it records was of very moderate dimensions. This valley was of course formed while the river ran at a lower level, but the erosive work accomplished at that level was surprisingly small. As the continental shelf is narrow along this part of the coast, the river may be supposed to have promptly graded its channel to harmony with the depressed base-level, and the conditions would seem to have been favorable for the development of a broad and branching valley like that submerged in Chesapeake Bay. The fact that no such development took place seems to indicate either that the lowering of base-level was small or that the period of low base-level was short. Despite the great volume of the river, the valley developed by the discharge at lower level was quite insignificant in comparison with the fiords and channels of the neighboring glaciated coast.

These features would have an important bearing on the question of low base-level in the district of the inside passages if we could be sure that the history of the Columbia estuary was really pre-Pleistocene; but there is reason to suspect that the Columbia has somewhat recently come into possession of the lower part of its valley. After passing the Cascade Mountains it turns northward in the great structural valley which farther south contains Willamette River and farther north holds Puget Sound. Then at the mouth of the Cowlitz it again turns westward, and traverses a low range of mountains or hills in a somewhat narrow passage. Close to the river these mountains have a height of 1,000 feet or more. From the mouth of the Cowlitz northward to Puget Sound the country is comparatively low, and the summits are occupied by

Pleistocene gravels. These features, while not demonstrative without further study, clearly suggest that the Columbia may formerly have followed the structural valley northward to and through Puget Sound, reaching the ocean by way of Fuca Strait. The occupation of the strait and sound by the great Pleistocene glacier would have compelled the river to find some different course, and when it had once carved a channel through the coastal hills the filling of its previous channel by glacial gravels would prevent its return to the earlier course.

In view of the possibility that the lower course of the Columbia dates only from the Pleistocene, it is evident that the character of its estuary has no decisive bearing on the problem of pre-Pleistocene base-level.

Summary. — Before the great glaciers of the Pleistocene began their work the district included a varied topography. The larger part was mountainous in the ordinary sense, with crests at various heights and a complicated system of steep-sided ridges, spurs and gorges. There were extensive remnants of a high-lifted peneplain, its plateaus marking the areas of most resistant rock, and above these plateaus rose summits of the nature of monadnocks. There were remnants of a low peneplain — a peneplain which is now near sea-level — and these occupied areas of relatively weak rock. There was a system of river valleys or master lines of drainage, narrow where the rocks were most resistant and more open among weak rocks. The bottoms of these valleys were in part below tide-level.

Glaciation

Rounding of Angles. — Turning now to the results of Pleistocene ice erosion, one of the most evident is the rounding of salient features. Where the slopes of mountain spurs have an average inclination as steep or steeper than that which permits the resting of talus, the inter-

mediate crest line is normally acute and serrate. The association of steep slopes with rounded summits is an abnormal condition requiring special explanation, and in glaciated districts there is a strong presumption that the rounding has resulted from the removal by ice of the salient parts of the spurs. The rounding, therefore, serves to show the extent of the district which has been subjected to glaciation. It also affords a rough measure of the depth to which the erosion has locally extended, for the imagination restores, more or less truthfully, the original sharp-crested form, and thus realizes the difference between that and the rounded form presented to the eye.

In the district under consideration the work of rounding has been extensive. Below certain levels the crests and profiles of hills, mountains and mountain spurs are devoid of crags and sharp angles and have curved outlines. From this general rule there are no deviations within the range of our observation, except where it is evident that the forms of glacial sculpture have been modified by later work of torrents or breakers. The rounding is more thorough at low levels than at high. Near its upper limit it often amounts only to the removal of pinnacles and the blunting of angles which would otherwise be sharp; farther down it has not infrequently been carried so far that no suggestion remains of the pre-glacial forms. In many places the depth of rock pared away in the mere smoothing of a rough topography must have amounted to several hundred feet.

The upper limit of rounding was estimated to range from 3,000 to 5,000 feet in the region of the inside passage, and these estimates are in substantial agreement with data given by the maps and photographs of the Canadian Boundary Commission. From the latter I estimate the height at 4,500 feet near Behm Canal (fig. 63) 4,000 feet near Berner Bay (fig. 62), 5,000 feet above

Chilkoot Lake (fig. 77), and 3,500 to 4,000 feet near Brady Glacier (fig. 61). In the neighborhood of Sitka it is about 2,000 feet.

In a general way this limit records the extreme height locally attained by the confluent ice of the Pleistocene. As the line often runs among modern névés and glaciers, where glacial erosion has been in progress ever since the maximum ice flood, there is possibility that the later development of cirques has, in places, carved out sharp blades and pinnacles from summits that had been rounded by the earlier flood, but this qualification is not believed to be important. The upward diminution of the paring of salient angles is such as would naturally obtain near the upper limit of ice action.

My observations of the limit of rounding are not so distributed as to give a comprehensive picture of the extent of the maximum ice-sheet, but they agree fully with Dawson's conclusion that the whole district was occupied. Where now are sounds and channels the ice depth was probably from 3,000 to 6,000 feet, but many summits were ice-free. Some of the uncovered peaks were nunataks, about which ice currents parted to unite again. Others were the culminating points of mountain masses which served as centers of glaciation.

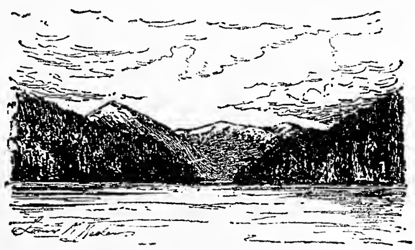


FIG. 67. A FIORD OF THE INSIDE PASSAGE.
The tops of distant mountains were smoothed and blunted by overriding ice.

Cirques. — Other features due to ice sculpture are cirques. These occur at all altitudes above 1,000 feet, being most abundant in the higher regions. Those above 3,000 to 3,500 feet now contain névés, and it is probable that they have been occupied not only since the last maximum of

glaciation, but in interglacial epochs and during a part of pre-glacial time. Therefore, only a part of the erosion they represent can be ascribed to Pleistocene ice. Those at lower levels were made under Pleistocene conditions and belong strictly to that epoch. It is noteworthy that they occur considerably below the upper limit of ice sculpture; on Kupreanof Island and in Glacier Bay they were seen on the flanks of mountains whose summits are well rounded. Though these lower-lying examples are less fully developed than those about the higher summits, they represent a notable amount of ice work, and that ice work was performed during stages of glacier development intermediate in extent between the modern and the maximum.

Fiords and Hanging Valleys. — The fiords admit of a partial classification as longitudinal, or strike, and trans-

FIG. 68. A FIORD OF THE INSIDE PASSAGE.
Ice-rounded mountains in the distance.

verse. Where the courses are direct and accord with the general trend of the coast, and especially where two or more fiords or channels are parallel, it is fair to assume that their positions were determined by structural factors. Where the courses make wide angles with the trend of

the coast, and are in detail characterized by short turns, it may be assumed that they are independent of strike. In the case of strike fiords, erosion may have been favored by the presence of weak rocks, but the erosion of transverse fiords had no such aid. Our best opportunities for direct observation were of fiords that either probably or possibly follow the strike, and the discrimination of aqueous and glacial erosion, or the problem of the amount of glacial excavation, is thus complicated by a factor involving much uncertainty.

Discovery Passage and Johnstone Strait, separating

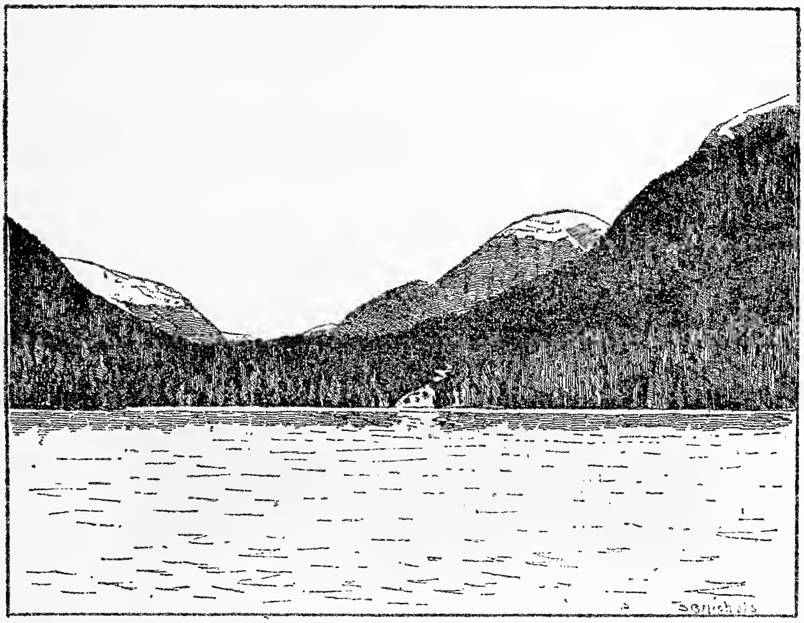


FIG. 69. HANGING VALLEY ON VANCOUVER ISLAND.
Photographed from Johnstone Strait. In the distance, an ice-rounded summit.

part of Vancouver Island from various minor islands and the mainland, constitute a well recognized fiord for 70 miles. With little exception, its walls of rock are steep at the water's edge and for some distance above and below. The central depth of water ranges from less than

200 to more than 1,000 feet. The immediate walls are 1,000 to 2,000 feet high, curving back to rounded summits. On the mainland side the fiord is joined by many troughs of similar depth and character, and by a few hanging valleys. From Vancouver Island it is joined by many hanging valleys. The sills of the hanging valleys best seen lie from 200 to 500 feet above tide and are evidently carved from the rock. Below each sill the contours of the main trough are continuous, without any deflection toward the side valley, and the draining stream has only begun the work of grading its channel. A shallow trench is cut on the edge of the sill, and escaping from this, the water tumbles down the open face of the fiord wall. Other valleys hang so high that from our low point of view we could not look into them. At a moderate estimate the highest seen are 1,000 feet above the water, and as these occur opposite the deeper part of the channel it is probable that the maximum discordance of valley floors is not less than 2,000 feet. All the hanging valleys appeared to be steep-sided glacial troughs, and those we saw best are at least several miles in length, with mountains behind them.

For this complicated system of troughs I have not been able to suggest an origin that does not involve an immense amount of excavation by ice. The hypothesis demanding least of the ice is one which assumes the main fiord to follow a belt of weak rock, in which pre-glacial streams had sunk their beds rapidly, outstripping such small tributaries as had strong rocks to contend with. Under such conditions, all pre-glacial valleys, with the possible exception of those in the weak rock, would have been narrow gorges, and the work of the ice in enlarging them to existing dimensions would be at least as great as the preceding work of the streams. While this work was being done by the tributary glaciers, the trunk glacier may

readily have carved from the weaker rock all that part of the fiord trough lying below tide-level.

The hanging valleys seen on Vancouver Island were evidently shaped by ice currents originating on the island and directed toward the mainland. During their existence the island contained a center of ice distribution. The general condition of the district at this time has been worked out by Dawson from studies of the striæ and other features of ice sculpture, made along the coasts of Vancouver Island, of the neighboring mainland, and of various smaller islands in the intervening sound. The principal flow of ice was from the mountains of the mainland, taking the form either of wide individual streams or of a great confluent sheet; and this flood, banking against Vancouver Island, was divided and deflected. One great division, the 'Queen-Charlotte-Sound Glacier,' moved northwestward to the ocean, spreading over the north end of the island. The other great division, the 'Strait-of-Georgia Glacier,' moved southeastward and then turned westward to the Strait of Fuca.[1] It is probable, also, that a branch of this stream, reinforced by tributaries from the Cascade Range in northern Washington, flowed southward as the Puget Sound Glacier.

FIG. 70. HANGING VALLEY ON PRINCESS ROYAL ISLAND, B. C., SEEN FROM FRAZER REACH.

[1] Additional observations on the Superficial Geology of British Columbia and adjacent regions. By George M. Dawson. Quart. Jour. Geol. Soc. London, vol, XXXVII, p. 278, 1881.

The thorough rounding of crests on Vancouver Island extends so far above the floors of the observed hanging valleys as to indicate that their glaciers were not features of the stage of maximum glaciation. It is quite possible that the greatest flood from the mainland turned back the feebler streams originating on the island and sent currents, here and there, through mountain passes to the southwestern coast.

Along the narrow passages separating Princess Royal and Pitt islands from the mainland, hanging valleys are equally abundant, and the illustrations of the physiographic type are even more striking. The greater tributary valleys approach the

FIG. 71. HANGING VALLEY, FRAZER REACH.
Ice-rounded summits in the distance.

fiords from the mainland and have sills near water-level, some of them lying so low as to contain shallow bays. All of the sills on the side of the islands are above tide, and the valleys back of them are surprisingly broad when considered as the channels of glaciers originating on islands only fifteen to twenty miles wide. The change of grade from the floor of the hanging valley to the side wall of the main valley is so abrupt as to give the impression that the sill is really a parapet, and that the alcove in the fiord wall contains a basin. At one point (fig. 70) we climbed to a sill with the half expectation of discovering a lake beyond, but found only the uneven, and in places marshy, floor of an ordinary U-trough. The highest sills seen are about 1,000 feet above tide.

As Grenville Channel, the passage separating Pitt Is-

land from the mainland, is straight, and as it has a parallel on the opposite side of the island, it is confidently classed with the strike valleys. At each end it connects with much wider fiords of the mainland, having the crooked courses of transverse valleys. From these relations I infer that the pre-glacial master drainage was transverse, and that the Grenville valley was not followed from end to end by a pre-glacial stream, but contained two streams, flowing in opposite ways from a medial summit. The passage about Princess Royal Island is not clearly marked as a strike valley, but its narrowness as compared with the transverse valleys in which it ends indicates that it originally contained two minor streams, with a summit between. No trace of either summit has survived the glacial remodeling. As in other fiords, the bottoms are irregular, but some of the lowest points lie midway between the ends. In fact, the deepest soundings reported in the two passages (severally 800 and 900 feet) are near their middles, and are not exceeded by recorded soundings in neighboring waters. When it is considered that these fiords, being parallel to the coast, run athwart the general movement of the ice from land to sea, the fact that their depth is comparable with that of troughs lying in the direction of general movement is certainly remarkable. It probably depends in part on the presence of a belt of easily eroded rock, but after all allowance for such favorable condition, one is impressed by the ability of ice

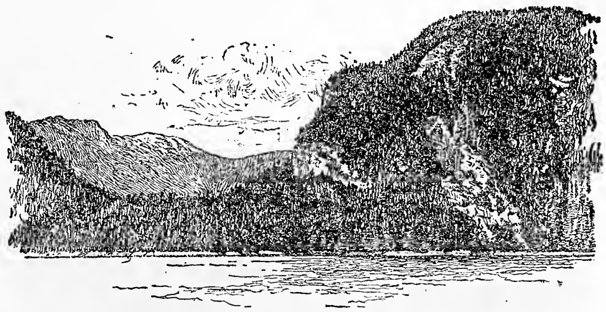


FIG. 72. HANGING VALLEY, FRAZER REACH.

to cut down its bed far below the profile which limits the action of running water.

The essence of the explanation is contained in Gannett's theorem that the glacier-made valley is homologous, not with the river-made valley, but with the channel made by the river. The bottom of a river channel is not evenly graded like its flood plain, but it abounds in hollows and hills, and the bottom of a glacier channel has irregularities that are similar but on a larger scale.

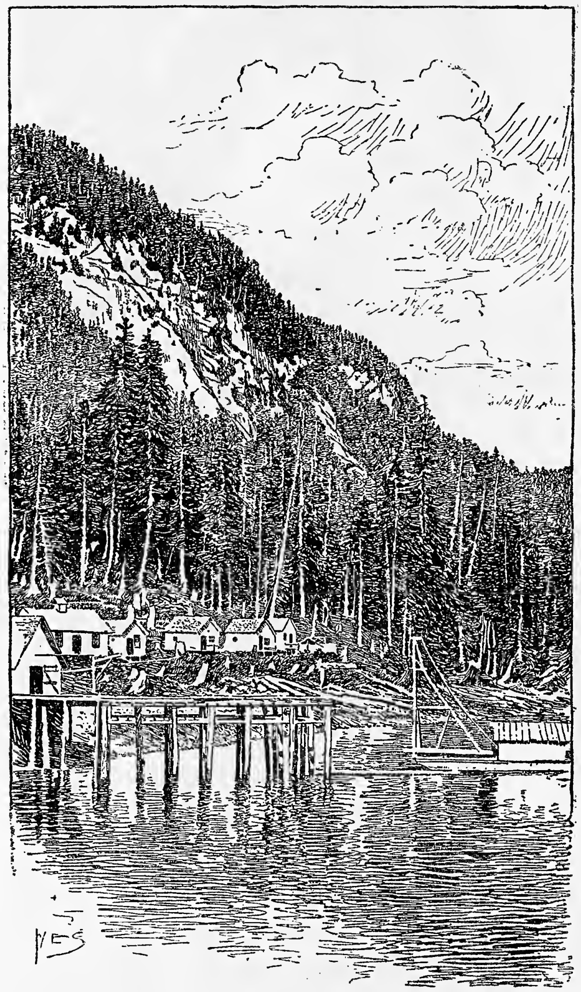


FIG. 73. NORTH WALL OF LOWE INLET.
The inlet occupies a glacial trough entering Grenville Channel from the east.

A phase of the Pleistocene condition of these passages is illustrated along the base of the Fairweather Range from Icy Cape to Cape Fairweather. A foothill ridge, 35 miles long, is separated from the range by a nearly continuous groove. A dozen alpine glaciers descend to the

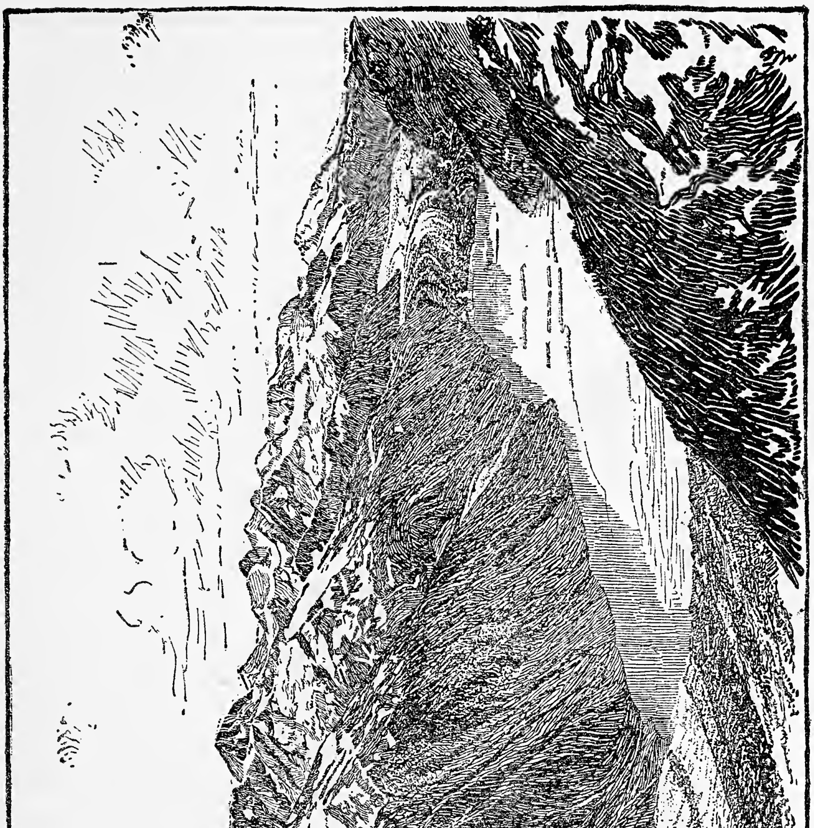


FIG. 74 HEAD OF LITUYA BAY.

groove and are there gathered into trunks which follow the groove lengthwise till escape is found through some break in the ridge. The surfaces of trunks and tributaries are mutually adjusted where they join, but it is easy to imagine that the progressive erosion of their beds is related to the volumes of the glaciers, and that the greater ice streams have the deeper channels. It is interesting to note in this connection that the bottom of this trough is below present tide-level — at least in part — in spite of the fact that there has here been a post-Pleistocene elevation of land. Figure 74 shows a portion of the trough where it is occupied partly by glaciers and partly by an arm of the sea. The observer stands on the foothill ridge. Lituya Bay has the form of a letter T, the cross-bar appearing in the view, and the shaft running through the foothills at the right. The large glaciers in the distance and foreground reach the longitudinal groove from deep mountain gorges. A small glacier, whose end barely touches the water, cascades over a sill that may be 800 feet above tide. A hanging glacier at 2,000 feet or more sends a tongue down a shallow groove in the steep wall of the fiord. And, at the extreme left, a pocket glacier occupies a hanging valley at an altitude of 3,000 feet.

The depth of the glacial excavation in the passages by Pitt and Princess Royal islands was probably about as great as in the passage by Vancouver Island. The scale of the topography is not far different, the evidence from hanging valleys is equally cogent, and the case is strengthened by the presumption in favor of pre-glacial summit levels. Even with a low base-level it is not at all probable that pre-Pleistocene streams carried the erosion of any considerable part of these troughs below present sea-level, and the water partings within them may well have been a thousand feet higher.

One of the more important passages of the Alexander

Archipelago is so direct in its course that a straight line 190 miles in length could be laid out upon it without touching either shore. It heads in the mainland at the extreme north and, trending a little east of south, terminates in the Pacific coast. The southern three-fifths, which bears the name Chatham Strait, has an average width of about seven miles; the northern two-fifths, known as Lynn Canal, averages five miles. Our direct observation was restricted to the northern part.

This straightest of all the passages is also deepest. No soundings have yet been charted for the southern third, but those of the northern part indicate that a continuous channel can be traced with 700 feet as its minimum depth, and the maximum depth, as already mentioned, is 2,900 feet. The bounding mountains, so far as we saw them, are 4,000 to 5,000 feet high, and the full depth of the trough is in the neighborhood of 6,000 feet. At its head the trough divides into four parts, which penetrate the upland, first as fiords or inlets and then as river valleys. These parts diverge from their point of junction like the ribs of a fan, their directions ranging from north to northwest; and their courses are remarkably straight, especially in the lower parts.

The unusual straightness of this great trough naturally suggests that its course was determined by some structural feature, such as a fault or the outcrop of an easily eroded rock. Its breadth is in better accord with the second of these tentative explanations; but the matter is not free from doubt. If the trough is a strike valley, we should naturally expect to find parallel valleys associated with it, but the number of such is limited. A short parallel trough lies fifteen miles west of Lynn Canal and contains Excursion Inlet. East of Chatham Strait are Seymour Canal and Stevens Passage, which are approximately parallel. But a number of other features

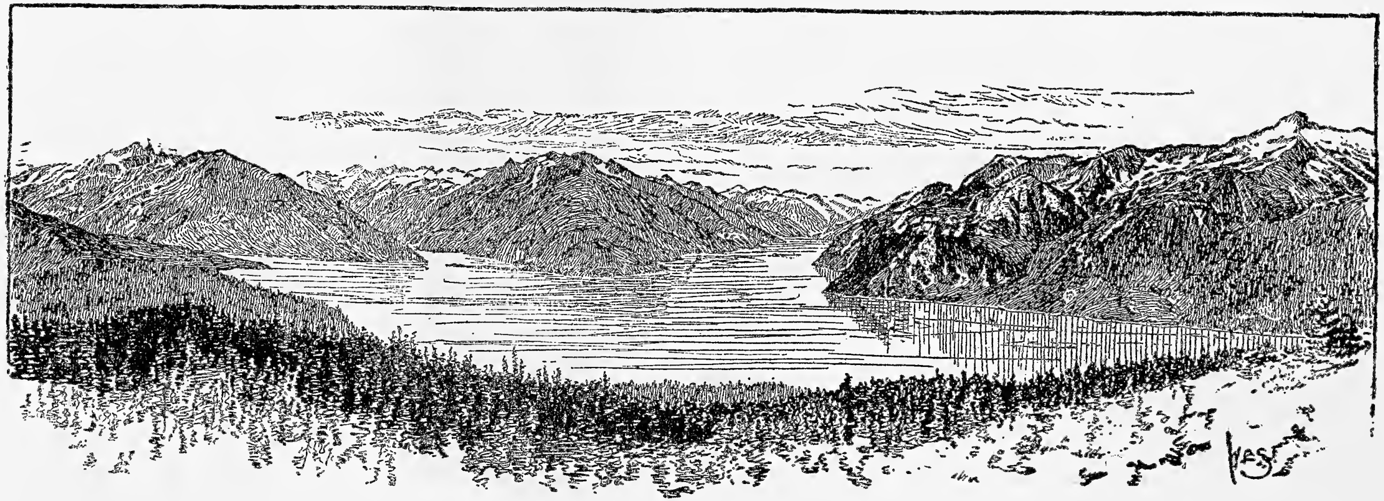


FIG. 75. HEAD OF LYNN CANAL.

We look up the canal from the peninsula between its main division and Chilkat Inlet, and see its other branches, Chilkoot (at left), Ferebee and Taiya. Each is occupied in part by the sea and in part by a river. The Chilkoot contains also a lake (fig. 77). The visible part of Lynn Canal is 2½ miles wide and 440 feet deep; Taiya Inlet has a central depth of about 1,400 feet for several miles, where its width is only 5,000 feet.

The peaks at the extreme right and extreme left, 5,200 and 5,000 feet high, project slightly above the zone of ice-rounding. The depth of Pleistocene ice in Taiya Inlet was not less than 6,000 feet.

in close association exhibit a systematic northwest trend; these are Icy Strait, Freshwater Bay, the main part of Tenakee Inlet, and Peril Strait with its prolongation in Hoonah Sound. The divergence of the branching fiords at the head of Lynn Canal is also perplexing; for, while each of these is so straight as to suggest an origin connected with strike, they are not parallel, but diverge fanwise from a common point.

The walls of Lynn Canal are well-defined features. At the water's edge and for some distance above, their contours are simple. There are few bays and no jutting promontories. The slope of the walls is not so steep as in some fiords; it rarely exceeds 45°, and in places is as low as 30°. Near the head of the canal the walls are well defined up to an altitude of about 2,000 feet, the height increasing toward the north and decreasing toward the south. Higher up, the mountains exhibit a varied topography: There are U-shaped troughs ending as hanging valleys at many different heights; there are V-shaped gorges modified at bottom by glaciers and separated by narrow tentiform spurs. These troughs, gorges and spurs approach the canal wall at all angles and there end. Sometimes they end abruptly, sometimes with a certain amount of prolongation down the steep wall; but this prolon-

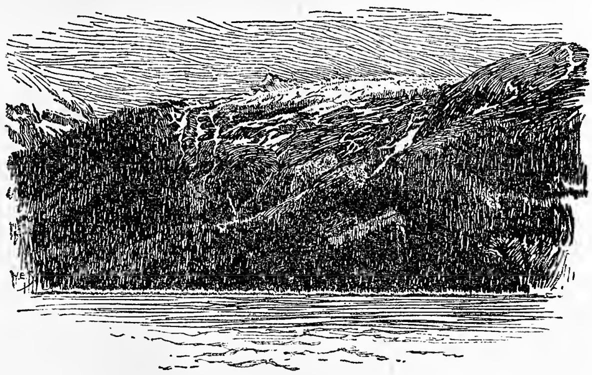


FIG. 76. HANGING GLACIER, TAIYA INLET.

The sill of the hanging valley is 3,500 feet above sea-level. For more than 1,000 feet below the glacier the fiord wall is kept bare by falling fragments of ice.

gation never extends to the water, and usually does not affect the slope within one or two thousand feet of the water. Their relation is such as might arise if the topography of the upland had formerly extended farther in the direction of the main trough and afterward been truncated by the development of the trough.

The branch troughs which unite to form the canal have similar walls, which rise higher before meeting the varied topography of the upland. They are also narrower, and at least two of them contract in their upper parts so

FIG. 77. NORTHEAST WALL OF THE CHILKOOT TROUGH.

Below is Chilkoot Lake, and beyond are Chilkoot Inlet and Lynn Canal. The lower part of the mountain was shaped by a great Pleistocene glacier, the upper by small tributaries, which survive. The summits are ice-rounded nearly or quite to 5,000 feet. The floors of hanging valleys are at 3,500 to 4,000 feet.

that the cross-profile is more nearly a V than a U. Skagway Canyon, a tributary to the Taiya trough, is narrow at bottom, except where occupied by alluvium. Glaciation has smoothed its walls on a grand scale, and has degraded its bottom enough to render the floor of a tributary discordant to the extent of 50 or 100 feet, but the type of cross-section acquired from pre-glacial stream erosion has not been destroyed. Photographs show that the upper

part of Taiya Valley has a similar character, and it seems to me probable that these gorges have been only moderately deepened by glaciers. The pre-glacial stream grades which they suggest would pass below present tide-level before reaching the head of Lynn Canal, and would be adjusted to a quite low base-level at the south end of Chatham Strait.

The bottom of the main trough is characterized by much

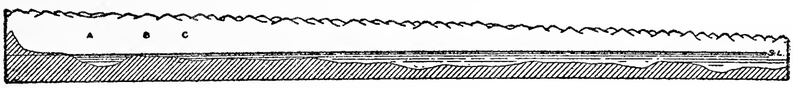


FIG. 78. PROFILE FROM TAIYA PASS SOUTHWARD.

The profile follows the lowest line through Taiya Valley, Taiya Inlet, Lynn Canal and part of Chatham Strait. Whole distance 165 miles. Vertical scale about ten times the horizontal. Base line 3,000 feet below sea-level. The approximate height of mountains east of the trough is indicated.

irregularity. The line of deepest water is sinuous and often wanders far from the middle, and along this line the depth varies irregularly (fig. 78). The soundings are

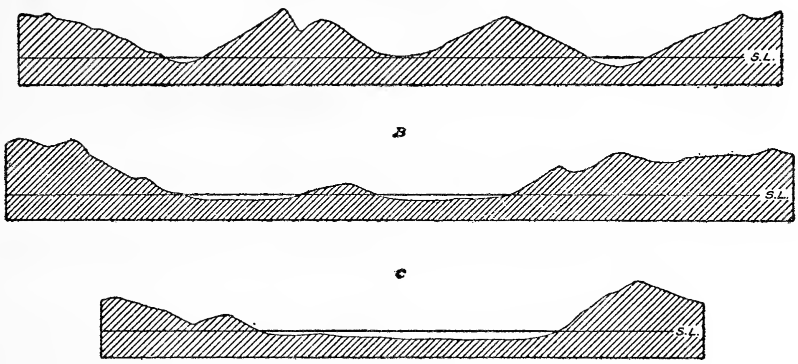


FIG. 79. CROSS-PROFILES ABOUT HEAD OF LYNN CANAL.

Based on contour map by Canadian Boundary Commission and soundings by U. S. Coast Survey. The positions are indicated by corresponding letters in figure 78. Profile *A* crosses Chilkoot Lake (fig. 75), Ferebee Inlet and Taiya Inlet. Profile *B* crosses Chilkat Inlet, near Davidson Glacier, and Lynn Canal. Profile *C* crosses Lynn Canal below Sullivan Island. S. L., sea-level. Base line 3,000 feet below sea-level. Vertical scale same as horizontal.

too far apart to give expression to details of configuration, and we do not know to what extent the irregularities may

be ascribed to unequal deposition of drift, but there is reason to believe that much of the inequality pertains to the rock floor and is to be ascribed to glacial erosion as conditioned by varying resistance of the terrane. A number of islands and one long peninsula are so placed that they may properly be regarded as portions of the trough bottom which rise too high to be covered by the sea. They are of rock, are thoroughly glaciated, and their axes, as well as all flutings and other lines of sculpture, are parallel to the fiord walls. Ice erosion has gone so far as to destroy all semblance to the forms characteristic of aqueous sculpture. Several islands and the southern part of the peninsula are shown in figure 3, and the view in figure 75 was made from the summit of the peninsula, 1,750 feet above sea-level.

From these various facts, as well as from general impressions to which it is not easy to give definite expression, I would draw the following tentative inferences: The V-gorges at the heads of branches of Lynn Canal and in the uplands bordering the canal, were made chiefly by pre-glacial streams, and they have been but moderately deepened by glaciers. There was a pre-glacial, comparatively narrow, valley through Lynn Canal, the floor of the valley being below present sea-level and related to a low base-level. Lateral V-gorges were tributary to this and were largely adjusted to it in grade. The Pleistocene glacier broadened the river valley, truncated the side spurs and the tributary gorges, and at the same time materially deepened the valley for the whole breadth of the trough. The glacial degradation is conceived as averaging hundreds of feet and possibly more than one thousand.

The lateral valleys so situated as to carry glaciers under other than Pleistocene conditions, are thoroughly shaped in characteristic U forms, and they now contain glaciers.

There are also valleys which are now free, or nearly free, from ice, and which were filled with ice only in the presence of the great glacier, and these have less characteristic glacial forms. It would seem that the presence of the great glacier in Lynn Canal gave them so high a base-level that their ice streams were sluggish and had little power of erosion.

The valley of Davidson Glacier deserves special mention as an illustration of the broad contrast which may exist between the systems of currents associated with different stages of glaciation in the same district. The névés supplying the glacier are not in sight from Lynn Canal, but lie back of the first line of summits, and the ice river flows eastward through a lateral or transverse valley, entering the great fiord approximately at right angles. During the great ice flood the general direction of movement was toward the south, and Davidson Glacier did not exist; its valley was not only filled with ice but overridden. It results that the upland bordering the Davidson trough in the vicinity of the Lynn trough, is planed and fluted with lines trending southward, while the Davidson trough, being shaped wholly by the Davidson Glacier during epochs of moderate ice supply, has an entirely independent sculpture, the lines of which are transverse to those of the overlooking upland. The Davidson trough is a fine example of its type. So far as visible from the sea, it is of uniform width; its parallel walls sweep in a simple curve of large radius and are steep. Although the topography just above and back of them is varied, they themselves have neither salient nor reentrant angles. The glacier has evidently adjusted its channel quite completely to the conditions of its flow, and has at the same time sunk itself deeply into the mountain it traverses (see fig. 2).

The transverse troughs of the mainland we did not

visit; they are known to me only through photographs, the contour maps of the Canadian Boundary Commission, and the soundings of the United States Coast Survey. As already mentioned, they are judged to be transverse to the strike, because they make wide angles with the general trend of the coast and because they are characterized by many short turns (fig. 80). Being independent of strike, their courses are also independent of variations in rock texture, and this character makes them specially available for the study of glacial erosion. Their walls are steep; photographs give the impression that they are decidedly steeper than those of Lynn Canal and its branches, but this impression is possibly due to the tendency of photographers to select localities exhibiting bold scenery. The walls stand well apart, after the habit of glacial troughs, and exhibit notable parallelism (fig. 62). Hanging valleys abound, ranging in height up to 3,000 feet or more and being more numerous at the greater altitudes. Some, like the Stikine and Whiting, are occupied by rivers; others, like the Taku, Speel, Unuk and Skeena, contain rivers in their upper parts and admit the sea below; others, like Tracy

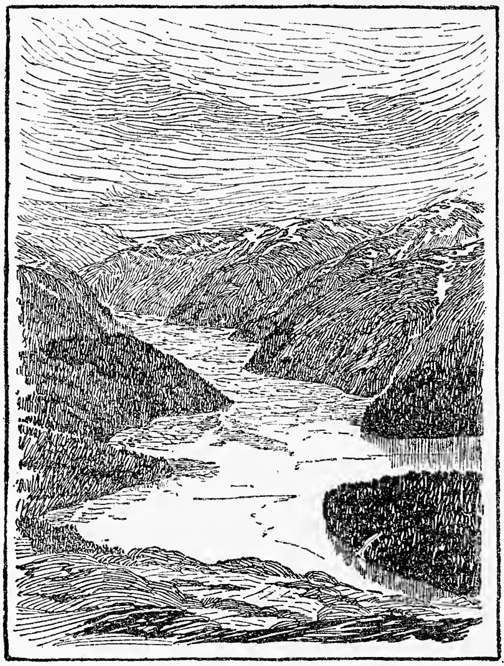


FIG. 80. MOUTH OF SPEEL RIVER.

The river is rapidly filling its deep trough with alluvium. Glacial rounding extends above the base of clouds, which cut off the view at about 3,000 feet.

Arm, Behm Canal and Portland Canal, have the character of fiords through their whole extent. Where rivers flow through them, the whole width from wall to wall is occupied by alluvium, and a lace-work of channels indicates rapid deposition. The open water has the depth, and the irregularity of depth, characteristic of fiords. In Tracy Arm, which has a breadth of one mile and a length of twenty, the soundings range from 850 to 1,150 feet. The main part of Behm Canal, with a width of two to three miles, has a depth ranging from 1,100 to 1,850 feet. In Portland Canal, which for eighty miles has an average width of two miles, the range of soundings is from 300 to 2,100 feet, and a depth of 1,200 feet occurs near the head.

It is scarcely to be doubted that all these long troughs were initiated by pre-glacial rivers; but the rivers could not have opened their valleys to the present width without giving time for the breaking down of the walls. If the river valleys were deep, they were also narrow, and their widening was the work of the Pleistocene glaciers. In the work of widening, the more obstructive projections were removed and the contours of the walls were simplified. The amount of erosion necessary to convert the assumed V-gorges into the observed U-troughs is large, and the ice streams by which it was done could not have failed to wear down the floors of their channels at the same time. While it is quite possible that the downstream parts of the river gorges had been sunk below present sea-level, the greater part of the excavation below sea-level was probably performed by the glaciers.

Inequality of Glacial Erosion. — The great work which it has seemed reasonable to ascribe to ice in the deepening and widening of fiords and other troughs stands in striking contrast to the feebleness of ice erosion in other places, which permitted, for example, the preservation of the low peneplains of Annette Island and the

vicinity of Sitka. In the one case the depth of the erosion is measured by hundreds of feet, in the other by tens. To a certain extent inequalities of erosion were determined by inequalities of resistance, but as the rock of the low peneplain is not of notably resistant character, and the rock traversed by the transverse troughs is in part of highly resistant character, it is evident that this is not the dominant factor. To an important extent also differences of erosion were determined by differences in the depth and consequent pressure of the flowing ice. But I conceive that the most important of the variable factors was the velocity of the ice currents. At the height of the Pleistocene flood the snow-fields were on high plateaus and mountain masses, from which the ice crept in broad sluggish streams to the preexisting channels of drainage. In these channels it assumed the character of rivers, and the lines of pre-glacial water drainage became, in the main, the lines of Pleistocene glacial drainage. Along the deeper waterways the ice could flow more rapidly because its depth was greater, and its ability to erode was correspondingly increased. Thus it was that the old river gorges, being adopted as lines of flow by the ice, were widened, straightened and deepened, while the adjacent uplands received comparatively little modification. The remnants of low peneplain were preserved, despite the softness of their rocks, because they lay outside the lines of flow of the strong currents. The remarkable deepening of the fiords of the mainland is probably connected in part also with the fact that they were longer occupied by glaciers than were the channels of the archipelago. Many of them still have glaciers at their heads; others are flanked by glaciers which would descend and fill them should the climate swing but slightly toward the Pleistocene condition.

The more thorough rounding of salient angles at low

levels than at high is probably due to the concurrence of several causes rather than to a single one. First may be mentioned the difference in pressure. The rate of abrasion, and of other forms of erosion, is probably enhanced by pressure, and during the height of the glacial flood all low-lying surfaces were subjected to greater pressure than those at higher levels. A second cause is connected with duration. The coming on and the passing of each Pleistocene epoch of glaciation was probably gradual, and there were doubtless glacial epochs of less intensity than the maximum. Thus the crests of low hills were subjected to glacial wear for longer periods than those of high spurs, and the difference may have been very great. Some allowance may also be made for subsequent modification at high levels. Ever since the last great ice flood began to wane, the valleys between high spurs have been occupied by small glaciers, and these have tended, by the development of their valleys, to reduce the width of the separating ridges. Thus, while the rounding at low levels was still in progress, a work had been begun which tended to reduce the effect of the rounding at high levels.

Glacial Deposits. — In the narrower parts of the inside passages we saw no accumulation of glacial drift. It is possible that drift masses were concealed here and there by the dense forest, but usually the spaces between cliffs and other visible outcroppings of rock were not large. It is probable that drift masses are concealed by the water, and have share in the production of the irregularity of the bottom; and a few bars and dams which are known to interrupt the continuity of other fiords are presumably morainic. As it is natural that the routes of travel should avoid such obstructions, it would be rash to infer the absence of local moraines from our failure to observe them. The only important bodies of Pleistocene drift which we saw are on the shores of the Gulf of Georgia, where

several extensive banks of waterlaid material constitute terraces, both on the mainland and on the shore of Vancouver Island. These banks are flat-topped, and estimated to rise from 100 to 200 feet above the water. One of them was seen to overlap hills with distinctly glacial sculpture, and as they are from 50 to 100 miles within the limit of the glaciated district they must have been accumulated after the last ice maximum.

The glacial deposits we encountered are of trivial magnitude collectively, in comparison with the glacial erosion of which we saw evidence, and it was therefore inferred that the principal regions of glacial deposition lay outside the field of our observation. This inference agrees with the conclusion of Dawson that the ice-sheet embraced the entire Alexander Archipelago, together with all other islands of the coast except the Queen Charlotte, and that its outer margin was beyond the present line of coasts.

Associated Sea-Levels. — The question of the relations of sea and land at the time of the great Pleistocene glaciation is of much interest, and some considerations bearing on the question will be mentioned, although the evidence at present available is either indirect or negative. As glaciers are chiefly phenomena of the land, and as glacial erosion in this district has been carried far below the present sea-level, it is natural to assume that the sea-level associated with that erosion was much lower. A little consideration, however, will show that such a conclusion does not necessarily follow. The deepest known hollow ascribable to ice work is in Chatham Strait, and lies 2,900 feet below sea-level. At that point the total depth of the great glacier was probably 6,000 feet. It is commonly assumed that where a glacier enters a sea not deep enough to float it, a part of the ice, equal in weight to the displaced water, is upheld by the water, and the pressure of the glacier on its bed is correspondingly dimin-

ished. While I do not regard this assumption as valid,[1] I entertain it for the moment because it gives a minimum estimate of the pressure of the Chatham Strait glacier. If the then sea plane had the same height as the present, the pressure of the glacier would be modified, by assumption, by the sustaining power of 2,900 feet of sea water. This sustaining power is equivalent to about 3,300 feet of the total ice thickness, leaving 2,700 feet of ice to press upon the bottom of the strait; and such a pressure would manifestly be ample for the work of erosion. So far as our numerical data go, this locality affords an extreme case; and as the hypothesis of glacial erosion below present sea-level is not barred for this locality, it is probably not barred for the whole district.

Another consideration is connected with the reaction of the ocean on the front of the glacier. My own observations, though comparatively limited, are so accordant with Dawson's generalization that I accept with confidence his conclusion that the Pleistocene ice front lay outside the present coast line throughout practically the whole district. If the ocean had then its present level, it washed the ice front for hundreds of miles. The power of the ocean to waste a glacier by melting is ordinarily greater than the power of atmospheric agents, and along the present coast of Alaska is much greater. As the factors are complex, it would be difficult to give an analytic demonstration of this proposition, but it is easy to illustrate by an example. The great confluent glacier which filled Glacier Bay in the eighteenth century had a general depth of 1,000 to 2,000 feet along the axis of the bay, and rested with less depth on adjacent tracts of land. All through the nineteenth century it was depleted, its wasting being brought about partly by the sea and partly by atmospheric agencies. The sea not only melted back the

[1] See discussion in chapter III.

front for 35 miles, but disposed of a continuous accession of ice from the Muir, Grand Pacific, and other glaciers. Of that portion of the confluent glacier which lay upon the land, a part slid into the sea and was there melted, but another part, which happened to rest on comparatively flat surfaces, remained on the land and has been subjected to only atmospheric agencies of waste. These agencies have not yet completed its destruction, so that extensive patches of stagnant ice, receiving no accessions from névés, remain to testify to the comparative feebleness of the atmospheric attack. I think there can be no exaggeration in the estimate that the melting by the sea has exceeded by ten times the melting from direct insolation and the contact of warm air and warm rain. It is further to be noted that this work of the sea was performed in a land-locked bay, where water cooled by the ice tends to accumulate and is but slowly exchanged for the warmer water of the open ocean. On the outer coast, where the supply of warm water would be constantly renewed by currents, the melting power would be still greater.[1]

The warmth of the Pacific Ocean in this region depends chiefly on the great circling current of the North Pacific, a part of the planetary system of oceanic circulation which might be modified but would not be stopped by any causes we may suppose to have existed in Pleistocene time. All through the Pleistocene the melting power of the ocean along this coast must have been great, and it is not probable that glaciers could so far have withstood it as to advance in deep water. The features of another part of the Alaska coast, to be presently described, render it probable that the glaciers were checked by the oceanic melting somewhere in the belt of shallow water, and were com-

[1] Muir Inlet near the glacier is 7,000 feet broad and 500 feet deep. Here Reid found a general temperature, at all depths, of 38° F. The oceanic temperature in the Gulf of Alaska is 58° F. The water of the inlet is 6 degrees warmer than melting ice, that of the neighboring ocean 26 degrees.

pelled there to yield up their load of rock waste. We know, from the extent of Pleistocene erosion in this district, that the burden of rock waste was large, and wherever the moraines were built they made an important deposit. If the Pleistocene base-level had been the same as the present I should expect to find that deposit as a continuous bar, or string of linear islands, along the outer coast of the Alexander Archipelago and at various points farther south, but no such features have been described, and the coast seems to have an entirely different character. This consideration, though connected at present with only negative evidence, distinctly favors the theory that the sea-level associated with the greatest Pleistocene ice floods was considerably below the modern sea surface.

There is some evidence, on the other hand, of a comparatively high sea plane after the glacial maximum. Dawson describes an extensive marine deposit, reaching a height of 200 feet, on the east side of Graham Island, the most northerly of the Queen Charlotte group, and infers from its relations that it was contemporaneous with a development of local glaciers.[1] At Nanaimo, on the inner coast of Vancouver Island, he found shell-bearing marine clays, resting on glaciated rocks, at a height of 70 feet above the sea.[2] In Gastineau Channel is a narrow shore terrace at a height of 200 feet, and in an associated clay Dall found marine shells. At two, at least, of the localities the shells are of species indicating cold water, and each locality is on the border of a sound or channel which would be filled with icebergs by a moderate development of glaciers. If the phenomena all belong to the same chapter of Pleistocene history, they record an episode similar to that of the Champlain clays of the Atlantic seaboard.

[1] Quart. Jour. Geol. Soc. London, vol. xxxvii, p. 281, 1881.
[2] Quart. Jour. Geol. Soc. London, vol. xxxvii, p. 279, 1881.

The terrace about Gastineau Channel is rather conspicuous at Douglas, where the forest has been removed, and was detected at several points where the forest still stands, but I searched in vain for its continuation about the shores of Lynn Canal and Cross Sound.

HIGH MOUNTAIN DISTRICT

Between Cross Sound and Prince William Sound are high mountains visible from the sea. They are much loftier than those of the Inland Passage district, and probably comprise a number of distinguishable ranges, though their system is not yet known. A mass culminating in Mount St. Elias (18,100 feet), west of Yakutat Bay, has been called the St. Elias Alps, and this name is sometimes made to include the whole chain. A more easterly portion, culminating in Mount Fairweather (15,000 feet), is sometimes distinguished as the Fairweather Range. Opposite these mountains the coast line is comparatively simple, being interrupted by fiords at a few points only and having no important islands. From Icy Cape westward the mountain base is bordered by a low foreland, narrow at first, but broadening to ten miles at Alsek River and fifteen miles at Yakutat Bay and beyond.

Many alpine glaciers now creep down the face of the range and unite in plateau masses on the foreland, a few of them spreading to the sea. The foreland bears also a system of ridges, of peculiar type, which are believed to be morainic and of Pleistocene age. Mention has already been made of one of these in describing the La Perouse Glacier. The ridge against which that glacier crowds, at the point of our visit, runs parallel to the coast for about seven miles and has an actual height of 1,000 feet, as indicated on the map of the Canadian Boundary Commission. It is nearly straight, is steeper toward the

land than toward the sea, and is contoured on the seaward side by a terrace, which probably lies 200 to 300 feet above tide. At the single point of examination this terrace contains marine beds overlain by glacial gravel, and the ridge back of it appears to consist of unsorted drift. The clays, where seen in section, are in part level and in part disturbed (page 41). The completion of the moraine ridge was subsequent to the deposition of the clays. The undisturbed clays imply, by their position, a higher stage of the ocean, and the overlying gravels are more readily explained by assuming that the sea-level was still high at the time of their deposition. It seems to me probable that the moraine ridge was deposited when the sea stood several hundred feet higher than now against the land.

Toward the southeast the ridge ends against the side of the La Perouse Glacier, and the relations indicate that the glacier is wearing it away. At one time it probably extended considerably farther in that direction, but was so low as to be overridden by the modern glacier and thus subjected to erosion by it.

Lituya Bay, a few miles up the coast toward the northwest, penetrates the land for seven miles, dividing not only the foreland but a low outer range of mountains. Within the mountains its trough has fiord characters, and from the walls of the mountain gateway run two morainic ridges, parallel at first, but curving toward each other and descending so as to unite under water at the entrance to the bay. These were seen only from the ship's deck, but their character is unmistakable. They are steeper within than without, and their inner contours continue those of the passage through the mountain ridge. They extend somewhat beyond the general line of the foreland, making a pair of capes which embrace the outer part of the bay. Close to the mountains they have an extreme height of

1,000 feet above the sea, as indicated by the contours of the Canadian Boundary Commission's map.

Between Lituya Bay and the mouth of Alsek River are several other morainic ridges, more or less crescentic in form, and so related to modern glaciers as to indicate that they were formed by them at some earlier epoch, when the ice streams were greater than now. In some cases the modern ice seems to extend to the base of the morainic rampart, and in one instance ice projects through a gap in the rampart; but the height of the old moraines forbids the idea that they were adjusted to glacial conditions closely resembling the present. From a distant view some were judged to be as high as 1,500 feet, and the modern glaciers seemed merely to touch their bases, instead of pressing against their inner faces. Associated with them, and extending along the coast beyond them, are a system of terraces, the highest of which was estimated to be 500 feet above tide; and these suggest that the sea surface stood comparatively high when the moraines were built.

The fact that the old moraines rise far above the modern glaciers but yet inclose areas only a little larger than the modern ice is able to occupy, is notable, and doubtless has an important significance if rightly interpreted. The explanation which occurred to me is, that the extent of the old glaciers was restricted by contact with sea water. As already pointed out, a warm ocean, like the Pacific in the Gulf of Alaska, is a most efficient agent for the wasting of glaciers. The high specific heat of water, the freedom of the circulation by which warm water is brought to replace the water which has parted with its heat, and the great depth of the body of warm water on which this circulation can draw, all contribute to this efficiency. It seems to me entirely possible that if the greater glaciers descending from Fairweather Range in earlier times en-

countered the sea soon after reaching the basal plain, they may have been wasted so rapidly along the line of contact as to determine there a principal line of morainic accumulation, and the ramparts of the coast may constitute the record of a successful resistance by the sea to glacial invasion.

If this explanation is correct, the Pleistocene submergence of the coast probably extended considerably above the zone of terraces. The oceanic resistance determining the deposition of drift would not be effective after the moraine ridge had been built so high as to become a partition between ice and water, and the theoretic position of the old sea plane is therefore along or above the highest crests of the moraine.

The hypothetic conditions are similar to those at the foot of Davidson Glacier. If that glacier should shrink, and the sea-level should be lowered in Lynn Canal, the Davidson moraine, if composed wholly of rock débris, would survive as a crescentic rampart with a flat top; and if the ramparts of the Fairweather region are strictly homologous they should have broad and level crests. If, however, the Davidson moraine is not wholly built of rock débris, but consists rather of an apron of débris resting against a concealed ice slope, the resulting rampart, when ice and water are withdrawn, would have an acute crest, with uneven sky-line; but the crest, instead of representing the plane of the present water-level, would stand somewhat below it. In viewing the old moraines of the Fairweather coast I recognized a few local flat summits, but the general character of the crest line is acute and its height is not uniform. If, therefore, the relation of the old glaciers to the sea was like the present relation of the Davidson Glacier, the sea then stood much higher against the land than now — or else the land then stood lower.

Whether these old ramparts represent the limit of Pleistocene ice at the time of *maximum* glaciation is a question as to which there may be doubt, but I incline to the view that the affirmative answer is the true one. So far as I could judge from distant views, the rounding of rock ridges and crests, characteristic of flooding by ice, extends but a moderate distance above the surfaces of modern glaciers on this part of the coast, and indicates glaciers of about the same magnitude as are indicated by the rampart moraines.

On the northwest side of Dry Bay, which receives Alsek River, a single fragment of a high rampart was seen, and in association with it a terrace; but thence to Yakutat Bay the broad foreland is low, its flatness being relieved only by ridges of moderate height. About Yakutat Village and Ocean Cape, at the mouth of Yakutat Bay, some of these ridges were seen to be morainic, and it is supposed that the whole foreland is constituted of glacial waste, chiefly of waterlaid gravel. If high ramparts were formed along this portion of the coast they were afterward destroyed and the material carried seaward by later advances of the ice.

On the mountains near the head of Yakutat Bay are fragmentary terraces at various heights ranging up to 1,200 or 1,500 feet, but as they face the bay rather than the ocean, it is entirely possible that they are of glacial rather than marine origin. Hanging valleys occur on the eastern wall of Yakutat Bay and on the walls of Russell and Nunatak fiords. One of these, near Nunatak Fiord, is now occupied by a glacier which cascades for 1,000 feet down the steep wall of the fiord. The sills of these valleys range from tide-level to a height of 1,500 feet or more, and they tell of great erosion by the trunk glaciers. The associated rounding of topographic angles is carried higher above surfaces of modern glaciers than in the

vicinity of Mount Fairweather, and this character seems naturally related to the gentler declivity of the mountain front. The enhanced alimentation of Pleistocene glaciers would tend everywhere to increase their thickness and their rate of flow, but it is easy to understand that the greater resistance to flow encountered on a gentle slope would cause the thickening there to be more notable than on a steep slope.

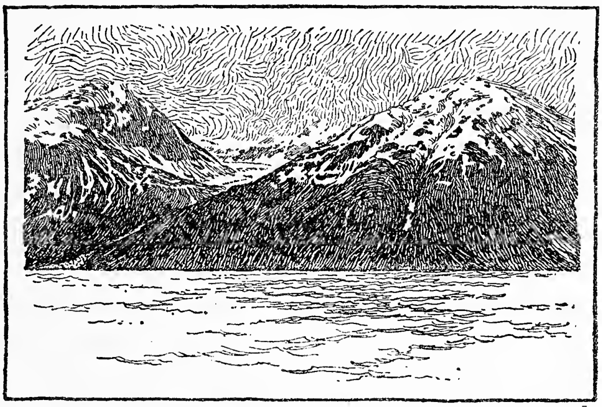


FIG. 81. HANGING VALLEY ON THE SOUTH SIDE OF NUNATAK FIORD.

So far as may be judged by the gradients of the neighboring Malaspina Glacier, the ice flood associated with the hanging valleys and rounded crests of the Yakutat region should have extended farther seaward than the line of the present coast, and it is probable that the outer morainic deposit is not visible. The submerged moraine ridges within the bay and across its mouth (page 49) pertain to quite moderate expansions of the Malaspina Glacier.

The inference that the sea-level associated with the moraine ramparts coincided with their highest summits may be interpreted in terms of land change or sea change. The local phenomena would be explained by assuming that the land has risen about 1,500 feet since the building of the moraines, or by assuming that the sea has subsided that amount, and it is, of course, possible that there have been changes of both land and sea, and that the discord-

ance of levels represents their sum or difference. While the question thus raised is not susceptible at present of a complete answer, it is nevertheless possible to make some progress in that direction.

In studying the Alexander Archipelago, which adjoins the Fairweather coast on the southeast, no evidence was found of a high sea-level in association with the greatest Pleistocene glaciers; but it seemed probable, on the contrary, that the mid-Pleistocene sea-level was considerably lower than the modern sea-level. Beyond the St. Elias Mountains, in the opposite direction, lies the district of Prince William Sound, and the Pleistocene history of that region appears to resemble closely that of the Alexander Archipelago. The Pleistocene history of the Fairweather-St. Elias coast thus appears to be exceptional and to be contrasted with the histories of neighboring coasts on both sides. This contrast is associated with a contrast in general geologic history, as revealed in the physiography. The district of the Alexander Archipelago is genetically a plateau, from which mountains and valleys have been developed by erosion. The district about Prince William Sound has been found by Schrader and Spencer[1] to have the same character and history. In each case a region of complex structure was reduced to a condition of low peneplain by long-continued erosion and then uplifted bodily though somewhat unequally. The original altitude of one plateau ranged from 3,000 to 7,000 feet, that of the other averaged 6,000 feet. The intervening tract has been lifted to a much greater height, so that its culminating peaks have altitudes of 15,000 to 19,000 feet, and it is probable that crustal deformation here produced mountain ranges directly, instead of creating a plateau from which they were developed by erosion.

[1] Geology and Mineral Resources of a portion of the Copper River district, Alaska. U. S. Geol. Survey, pp. 62–76, 1901.

Two facts indicate that these mountains are geologically young. The first is paleontologic. Russell found, in one of the lower spurs of Mount St. Elias, a fossil marine fauna composed wholly of forms which still inhabit the coastal waters of Alaska.[1] These show that the last great elevation of the mountain range is recent, as measured in terms of biologic evolution. The other evidence of youth is found in the great height of the mountains. As pointed out by Powell, the degradation of mountains is so rapid that only young mountains can be lofty. The St. Elias Range is not only lofty but steep, and its rate of waste must be rapid. The fact that it is lofty despite rapid waste indicates that its waste is compensated by growth.

In view of the differences in general geologic history, there need be no surprise if the Pleistocene history of the district of high mountains should differ from the Pleistocene history of the districts of Alexander Archipelago and Prince William Sound. In view of the loftiness of the mountains, it is rather probable than otherwise that uplift has occurred since the epoch of chief Pleistocene glaciation. It is therefore inferred with some confidence that the discordance between the sea-level indicated by the rampart moraines and the present sea-level has been brought about chiefly by local uplift of the land.

If this view is correct, the disturbed marine clays observed near La Perouse Glacier (fig. 22) may be connected with a fault zone of Pleistocene or post-Pleistocene date.

PRINCE WILLIAM SOUND

Prince William Sound is a very irregular bay, opening southward (pl. XIII). All about it are mountains, the higher being massed at the north, and others encroaching on its area as promontories and islands. The largest islands,

[1] National Geographic Mag., vol. 3, pp. 171–172, 1891.

Montague and Hinchinbrook, lie at the south, separating the sound from the open ocean. The inlets of the northern coast, some of which we visited, are fiords, abounding in evidence of glacial sculpture, and the lower slopes of the as-

FIG. 82. PENINSULA NEAR ORCA, PRINCE WILLIAM SOUND.
Shows the glacial rounding of mountain crests, fifteen miles from the ocean.

sociated peninsulas and islands are well rounded. On the east side of the sound the rounding extends to an estimated height of 3,000 feet, in Columbia Bay, at the north, to about

FIG. 83. HINCHINBROOK ISLAND, FROM THE SEA.
Shows a serrate crest line, little, if at all, modified by overriding ice.

4,000 feet, and to the same or greater height in Port Wells. Seaward the height diminishes and the higher crests of the outer islands are comparatively angular and serrate.

It is probable that Pleistocene ice occupied the whole sound, but nothing is known of its seaward limit.

In College Fiord, a branch of Port Wells already described (page 81), there is a magnificent system of hanging valleys, the larger being still occupied by glaciers, which enter the fiord with ice cascades. These side glaciers have accomplished something in the way of erosion since the disappearance of the trunk glacier to which they were once tributary, so that they do not rest upon the unmodified face of the fiord wall, but occupy shallow channels. In a general way the surfaces of the glaciers, in their lower courses, are flush with the adjoining portions of the fiord wall.

My attention has been directed by Gannett to the fact that several of the cascading glaciers make two leaps, and that there is a certain amount of harmony in the spacing of the falls. When the region shall have been thoroughly studied it is possible that the interpretation of these correspondences may develop a special chapter in the history of the ice retreat.

With the aid of a series of photographs made by Merriam, I have computed the approximate heights of the more important cascades, as follows: Wellesley, 1,700 feet; Vassar, 2,200; Bryn Mawr, (trunk) 1,300, (left branch) 2,700, (right branch) 2,500; Smith, 1,250, 1,700

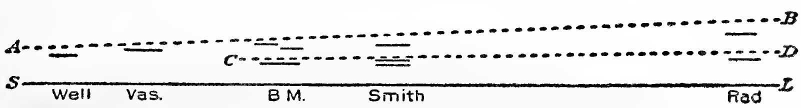


FIG. 84. DIAGRAM OF NORTHWEST WALL OF COLLEGE FIORD.

Short horizontal lines show the relative positions of the cascades of Wellesley, Vassar, Bryn Mawr, Smith and Radcliffe glaciers. S.L. sea-level. Scale, 14,000 feet = 1 inch. Compare figures 44 and 45.

and 2,600; Radcliffe, 1,800 and 3,500. When these are platted to scale in their proper vertical and horizontal relations (fig. 84) they fall into two series, descending southward from the head of the fiord. Making some allowance

for the greater volume of the side glaciers when the trunk glacier filled the fiord, I have indicated the profile of the trunk glacier by a dotted line (AB). The inclination of this line from the horizontal is about 2°, or one in twenty-five. Its height above tide ranges from 2,800 to 4,800 feet, and it indicates a thickness of ice exceeding these figures by the depth of the fiord, whatever that may be. In the line of Gannett's suggestion, a second tentative profile (CD) is drawn in similar relation to the crests of the lower series of cascades.

The depth of ice indicated by the hanging valleys is somewhat less than that which would be inferred from the rounding of projections, and it seems probable that the epoch during which the hanging valleys received their principal sculpture was not the epoch of maximum glaciation.

A cordon of high hanging valleys surrounds Harriman Fiord. Above Barry, Serpentine and Surprise glaciers they contain hanging glaciers at a general height of about 4,000 feet, and east of Harriman Glacier their ice banks coalesce in a continuous terrace along the valley wall (page 95). The surface of the trunk glacier to which they are adjusted probably lay 5,000 feet above present sea-level.

On the north side of Montague Island and at various points on the peninsulas of the east and west sides of the sound, a horizontal terrace was observed, at an estimated height of 50 to 75 feet above tide. No near view was obtained, and I did not learn its character.

As the Pleistocene glaciers extended at least to the outer coast line, as their work of erosion was great, and as their limit is not indicated by conspicuous moraines, the provisional inference is made, as in the discussion of the Alexander Archipelago, that the ocean surface was comparatively low at the time of their greatest expansion and that their outer moraines are now submerged.

KENAI PENINSULA

My observation of the Kenai Peninsula was restricted to the northwest side of its more southerly arm. It is there constituted by a lofty upland partially dissected by large trenches, some of which now contain glaciers. Its upper parts have a comparatively mature topography, and seem to constitute remnants of an ancient peneplain, which has been bodily uplifted, with some disturbance of original horizontality. The plateau resulting from this uplift was deeply trenched along the main lines of drainage, and the valleys thus opened were modified in characteristic manner by Pleistocene glaciers. They are now U-troughs, and some are partly submerged, so as to constitute fiords. On the side facing Kachemak Bay and Cook Inlet, it was evident that the old glaciers extended beyond the position of the modern coast line, but nothing was seen to indicate their outer limits.

KADIAK ISLAND

Kadiak Island is 100 miles long and 50 miles broad. Its longer axis, trending northeast, is parallel to the neighboring coast of the Alaska Peninsula, from which the island is separated by Shelikof Strait, 30 miles wide. Afognak Island, a close companion of Kadiak, continues its northeasterly trend; and the Barren Islands serve as physiographic stepping stones to connect the group with the axis of uplift following the oceanic side of Kenai Peninsula.

The island is mountainous throughout, but contains no lofty range. As on the Kenai Peninsula, the summits tend toward uniformity and an even sky-line, and there are remnants of an ancient uplifted peneplain. Such lowlands as we saw are of moderate extent and uneven surface. The coast line is sinuous, and some of the nar-

row bays may properly be designated fiords, although less strongly characterized than those of southern Alaska.

Opportunities for personal observation included near views of the northern coast, a brief landing near the western extremity, and a longer stay near the eastern extremity, with Kadiak Harbor as a base of operations.

Our landing at the west was on a part of the coast facing Shelikof Strait, west of Sturgeon River. The view was limited by a fog, but I was able to recognize two narrow U-troughs with simple contours. The ridge between them, composed of granite rock, was seen to have a narrow, straight crest; and a parallel ridge, less clearly revealed, appeared to be of the same character. The troughs were evidently shaped by glacial ice, and the narrowness of the intervening crest indicates that the chief work was done by valley glaciers, rather than by an overriding ice-sheet.

Thirty miles farther east we entered the mouth of Uyak Bay, a long inlet heading south of the middle of the island but opening northward. The mouth lies among hills or low mountains, whose thorough rounding indicates complete flooding by Pleistocene ice. Toward the interior I could see mountains, several thousand feet high, whose blunt summits told of ice-scoring, and beyond them loftier peaks with angular crests. The slopes bordering the bay descend steeply to the water, and there is no foreland, but the sweeping curves characteristic of the typical fiord are wanting. No accumulations of drift were seen.

Steaming north from Uyak Bay and then eastward, we passed two large projections of the coast, one a peninsula (Ugat) and the other an island (Uganuk), and the extremities of these were thought not to be glaciated. On the peninsula are hills with ragged summits, apparently crested by outcropping igneous dikes.

Straits separate the north end of the island from three

smaller islands, all mountainous. Traversing the straits, we found familiar signs of ice work: on Raspberry Island a straight wall with hanging valleys; on the Kadiak side a general rounding of all summits up to the clouds, which hung at about 2,000 or 2,500 feet. Here, too, the water is bordered in places by a lowland or terrace (fig. 85), carved, for the most part, from vertical slates. In detail the lowland is uneven, and it is locally broken into islands, but its general plane is easily traced and, as already noted by Dall,[1] inclines from east to west. The height ranges from about 100 feet to sea-level.

At the extreme east lies Chiniak Bay, a broad opening, invaded on one side by mountain promontories, and partly

FIG. 85. TERRACE ON SPRUCE ISLAND, OPPOSITE KADIAK ISLAND.

sheltered from the ocean by a group of low islands. Close to the islands is the village of Kadiak. The general trend of promontories and islands is northeast-southwest. The islands are shredded remnants of a plain carved from vertical slates, probably a base-level plain contemporaneous with the terraces along the straits (fig. 86). Their uneven surfaces include rounded hills about 100 feet high, but the plane of the original peneplain must pass above these.

All surfaces about the bay are glaciated. The island topography is moutonnée, with a large pattern, individual bosses being sometimes half a mile or more in length. A few patches of glacial polish and striæ were found, though such records have been generally obliterated by weather-

[1] Seventeenth Ann. Rept. U. S. Geol. Survey, Part I, p. 863, 1896.

FIG. 86. ISLANDS OFF KADIAK.

The observer stands on a promontory of Kadiak Island at a height of 1,000 feet and looks eastward. At the left is the village of Kadiak, built on a sloping foreland. Islands and foreland are remnants of a peneplain. See page 179.

ing. The valleys between promontories of the mainland are U-troughs. The steep hill back of the village, a mass of slate, is smoothed and fluted on a grand scale, its original topography being so completely remodeled that its drainage seeks new routes and is engraving narrow canyons across the rounded slopes (fig. 87). Northwest of this hill stands a higher ridge, where the upper limit of ice-rounding is seen to be about 3,000 feet above tide, and where several hanging valleys overlook a finely sculptured trough (fig. 88). It is evident that a confluent ice-sheet, enveloping all but the highest summits, here flowed to the northeast, with a thickness, along the present coast line, of 2,000 to 3,000 feet. No important masses of drift were seen.

While these observations cover but a small part of the island, they are so distributed as to throw considerable light on Pleistocene conditions. The glaciation of the eastern, northern and western extremities of the island, and the notable height to which ice sculpture extends at the east and north, indicate a practically continuous glacial envelope, from which scattered peaks projected as nunataks. Afognak and the other important islands of the group were probably included in the same envelope, and the ice extended in many directions beyond the position of the present coast line. The apparent absence of glaciation from salient features of the northwestern coast indicates

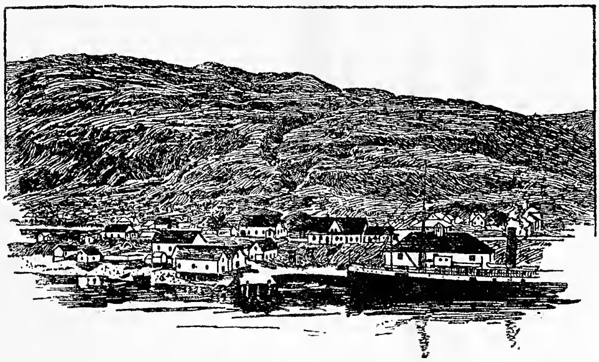


FIG. 87. HILL BEHIND KADIAK VILLAGE.
Showing glacial sculpture and subsequent erosion by a stream.

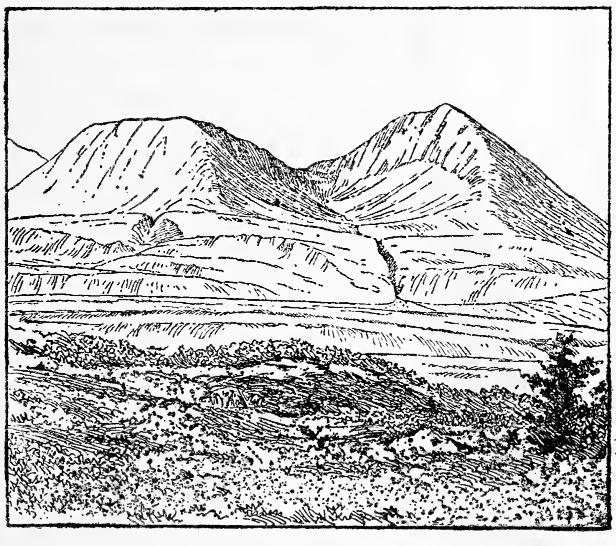


FIG. 88. HANGING VALLEY NEAR KADIAK VILLAGE.
The lower ground was shaped by a large glacier moving from left to right.

that the ice-sheet of the island was not an overflow from the mainland, for mainland ice could not have crossed the island without burying deeply the whole northwest coast. And the same interpretation may be given to the narrow-crested ridge observed between glacial troughs at the west, for a strong overriding current would have flattened the crest. The relation of land to sea in Pleistocene time is not shown, but remnants of a low base-level plain indicate a pre-Pleistocene period of stability, during which the attitude of the land was slightly different from the present, the eastern side of the island being somewhat lower than now.

The reasoning tending to show that Pleistocene glaciation was associated with a low sea-level applies to the south coast of Kadiak with even more force than to the district of Prince William Sound, for the island, standing forward beyond the general line of the Alaska coast, is specially exposed to the influence of the great ocean current.

REGION OF THE GULF COAST

Fragmentary as were our observations in the districts we have already described, they were still more fragmentary in those touched farther west and north, and the present is therefore a convenient point for retrospect and summary. The district of the Alexander Archipelago, the district of high mountains, the district of Prince William Sound, Kenai Peninsula, and Kadiak Island, circle about the Gulf of Alaska. A curved line passing through them is more than 1,000 miles in length, and its extremities are 900 miles apart.

In the high mountain region the Pleistocene glacial system seems to have included alpine glaciers similar to those of the present time but larger; and these united in a system of piedmont glaciers, or possibly in a confluent piedmont glacier, which everywhere reached the sea. In

the other districts the Pleistocene glaciers were confluent, extended beyond the line of the present coast, and probably reached the sea, although their limit is undetermined. In the high mountain region there has been post-glacial uplift of the mountains, and in connection with that uplift great moraines, which were probably formed at the water's edge, have become part of the land. In the other districts the apparent absence of similar great moraines is provisionally explained by the hypothesis that the sea surface then lay lower with reference to the land and that the subsequent submergence of a portion of the land has concealed the zone of morainic deposit.

Assuming that a change has transpired in the relation of land and sea since the epoch of maximum glaciation, it is of interest to inquire whether that change was a sinking of the land or a rising of the sea. The general theory of the subject has not yet reached such a condition as to afford a satisfactory answer, but, on the contrary, is so unsettled as to find advantage in every local determination of the nature of the change which may be made on independent grounds. In the case of the high mountain district, the geologic recency of orogenic movement is indicated in other ways, and the post-Pleistocene emergence of land is therefore referred with confidence to land change rather than water change. In the other districts we have no evidence of recent orogenic change, and the mountains appear to have been produced by the dissection of broad plateaus. The uplands about the Alexander Archipelago and Prince William Sound, and those of Kenai Peninsula and Kadiak Island, all contain traces of uplifted peneplains, the uplift having occurred so long ago that the resulting plateaus were profoundly sculptured before the advent of Pleistocene glaciers. The districts of the Alexander Archipelago and Kadiak Island are also characterized by peneplains near present sea-level; and

low terraces observed in Prince William Sound are possibly of the same order. It is, furthermore, probable that the pre-Pleistocene dissection of each area was continued in association with a comparatively low base-level. In view of the large number of common elements, the whole region, with the exception of the high mountain district, may be provisionally regarded as a unit in its later geologic history. The uplifted peneplains do not all stand at the same height, and there are important differences of altitude within individual plateaus. These local differences suffice to show that not all changes can be ascribed to the sea, and make it probable that the plateaus were created by changes originating within the earth's crust. The low peneplains also show minor discordances, and while these also must be ascribed to crustal movement, the fact that they are of moderate amount is, on the whole, indicative of general crustal stability. It is a noteworthy, and probably significant, fact that the oceanic base-level of the region, after resting for a long time at the height indicated by these low peneplains, dropped below them at the time of the excavation of the fiords and then returned to approximately the same position. If this oscillation was an oscillation of the land, it was of the broad or epeirogenic type, and the association of wide extent with approximate uniformity of position after the completion of the cycle is most remarkable. It would seem probable that so great a general movement of the earth's crust would afford opportunity for the relief of local strains, and thus be accompanied by important differential movements. On the other hand, sensible uniformity for any region of the magnitude here considered would theoretically be a characteristic of an oscillation of the sea. The local evidence, therefore, seems to me more favorable to the hypothesis that the sea was low during the fluvial and glacial erosion of the fiords and has

since risen, than to the hypothesis that the land was then high and has since subsided.

UNALASKA ISLAND

On two occasions we spent a few hours at Dutch Harbor, making short excursions in the immediate neighborhood, and we also sailed along the north coast on a foggy day. The opportunities for observation thus afforded were much more limited than those enjoyed by Russell,[1] and my notes are chiefly of service as affording verification of his description. The north coast, west of Cape Cheerful, is faced by a high sea cliff which testifies to rapid aggression by waves. The cliff shows in cross-section a number of U-shaped valleys, and these, so far as the fog permitted us to see them, have the simple contours characteristic of complete adjustment to the conditions of ice flow. Several of them end hundreds of feet above the sea, this condition being manifestly due to truncation by the receding shore cliff. One of them reaches the shore at tide-level, and the walls of that one seemed to be sheathed with a layer of drift in which post-glacial rills and brooklets have cut narrow gashes. The shore cliff also truncates, at rather high levels, a few V-shaped gorges, and the association of these with the glacial troughs gave the impression that the Pleistocene glaciers were of alpine type and not confluent. As the mountains were concealed by fog, I was unable to observe the cirques of which Russell makes mention.

The forms of the hills about Unalaska Bay are not typically glacial, but, on the other hand, they are not constructional (with a single exception), and if products of atmospheric waste, they are of unusual type. The single constructional form is a young volcanic cone near Cape Cheerful. The other hills are also of volcanic rock, but

[1] Bull. Geol. Soc. Amer., vol. 1, pp. 138–140, 1890.

give little suggestion of the original mountain forms from which they were derived. They are irregular alike in their larger and smaller features.

If the forms of land in this part of Unalaska Island were constructional, the sinuosity of the coast might be ascribed to irregularities of volcanic eruption; but as they are erosional, the deep embayments between steep-sided points and islands, and the dearth of plains near sea-level, point toward a somewhat recent subsidence of the land or rising of the sea.

Spurr describes a series of terraces near Unalaska Bay, ranging up to a height of 1,500 feet, ascribes them to marine action, and infers a gradual rising of the land in late Pleistocene time.[1] He notes also that the village of Iliuliuk stands on a spit which is evidently of recent formation but is shown by its vegetation to be above the reach of storm waves, and infers that elevation of the land is now in progress. The last mentioned observation I was able to verify, but I was not satisfied that any higher terrace I saw had been formed by the sea.

BERING SEA

The most extreme and contrasted opinions have been advanced with reference to the Pleistocene condition of Bering Sea. It has been stated by one high authority[2] that the western coast of Alaska, the eastern coast of Siberia, and various islands of Bering Sea, are all glaciated in such a way as to indicate the occupation of the eastern part of the sea by an ice-sheet; and it has been asserted

[1] Eighteenth Ann. Rept. U. S. Geol. Survey, Part III, pp. 266–267, 273, 276, 1898.

[2] John Muir. On the Glaciation of the Arctic and Subarctic Regions visited by the U. S. S. Corwin in the year 1881. Rept. Cruise of the Corwin, 1881, Washington, 1885.

by another high authority[1] that there are no evidences of glaciation, either general or local, on these various coasts and islands. A third investigator,[2] also of high rank, ascribes the fiords of the Siberian coast to glaciers, but finds no evidence of glaciation on the neighboring coast of Alaska about Port Clarence. My own opportunities for observation were limited to a few hours each on St. Paul, St. Matthew and Hall islands, a few hours sailing past the Siberian coast, with a brief landing in Plover Bay, a distant view of Cape York, a point southeast of Cape Prince of Wales, and a few hours on the tundra near Port Clarence. The scanty facts thus gathered can not be expected to settle the vexed question; but, in view of the wide diversity of existing opinion, it appears worth while to make record of even hasty observations and first impressions.

Of St. Paul Island we saw the southern peninsula. The land is there composed of remnants of volcanic cones

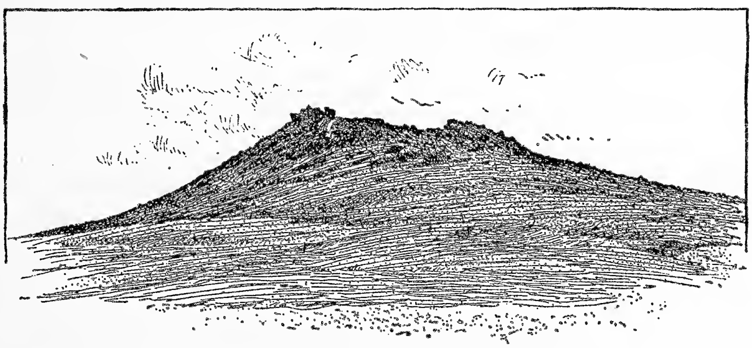


FIG. 89. CRATER RIM ON ST. PAUL ISLAND.
Shows projections which would not survive glaciation. Photograph by U. S. Coast Survey.

whose softened profiles indicate long-continued weathering. The forms are smooth, except where cut by the sea

[1] W. H. Dall. Bull. 84 U. S. Geol. Survey, p. 258, 1892. Alaska and its Resources, pp. 461-464, 1870.

[2] A. E. Nordenskiold. The Voyage of the Vega. New York ed., pp. 569, 583-585, 1882.

or varied by traveling dunes of lapilli. To my eye they conveyed no impression of ice sculpture; I saw neither the long parallel grooves and ridges which glaciers sometimes carve from homogeneous rocks, nor the groups of moutonnée bosses which they usually develop where rocks are of varied texture. On the main part of the island are younger cones with well-preserved craters, and photographs show that with these are associated crags such as an overriding glacier would not spare (fig. 89). Neither is it to be supposed that the craters themselves would survive the erosive action of a great ice-sheet. It may be affirmed with confidence that if the island was ever traversed by a glacier the crater-bearing cones are of later origin.

St. Matthew and Hall islands are also volcanic, but without constructional forms. The period of eruption was so remote as to give time for the complete subsequent remodeling of the surface by weathering and erosion. The coast shows a succession of cliffs, with rare bays and spits, and is evidently retreating rapidly before the attack of the waves. The higher slopes, though sometimes steep, are in general mature, and well adjusted to the conditions of erosion in a climate which obstructs the flow of water by clothing all surfaces with a sponge-like mantle of mossy and herbaceous vegetation. I saw nothing of the peculiar forms characteristic of glacial sculpture, but noted, on the contrary, a few blunt pinnacles projecting from the general surface and exhibiting such ragged details as one does not find in glaciated regions. Figure 90 represents one of these which happened to come within the field of a photograph.

The ordinary landing at Port Clarence is upon a long spit, but we visited the mainland also, going ashore at a point where a gently undulating surface rises within a few miles to hills several hundred feet high. The rock is

a highly inclined slate, and the shaping of the surface has been wholly by erosion. Except at the coast, the rocks are concealed by tundra. This spongy growth obstructs the flow of water, so that streams are rare; but we landed at one of these rare streams and had a view of its valley (fig. 91). The valley is evidently one of mature development, and its profiles are perfectly adjusted to the associated lines of drainage. The divides are broadly rounded, but the rounding is that characteristic of inter-stream summits where the vegetal mat is close, and is distinctively non-glacial. The bed-rock here has the same physical character as that in the Kadiak region, but the topographic aspect is altogether different. About

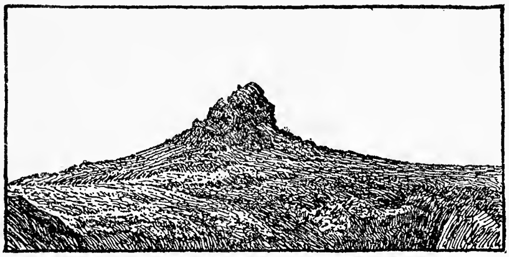


FIG. 90. UNGLACIATED KNOB ON ST. MATTHEW ISLAND.

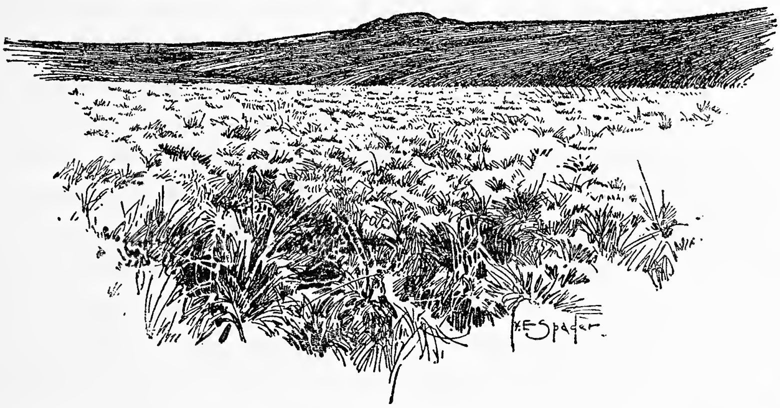


FIG. 91. STREAM-GRADED VALLEY NEAR PORT CLARENCE.

Kadiak the hills have moutonnée forms, the hills and hollows have a dominant trend, and the drainage is youthful. At the Port Clarence locality the topography does not

exhibit a dominant trend and all slopes are fully adjusted in harmony with the drainage.

The southeastern part of the Siberian peninsula is characterized by low mountains with spurs projecting seaward as promontories and alternating with fiord-like bays. The topographic details near the coast fall into three categories: (1) A system of relatively gentle slopes chiefly occupying uplands; (2) a system of relatively steep slopes chiefly exhibited in the walls of the fiords (at points of junction these are sharply contrasted with the slopes of the first system); (3) coastal features, especially shore cliffs and

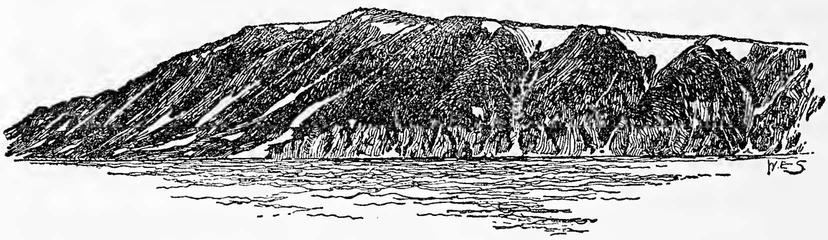


FIG. 92. EAST WALL OF PLOVER BAY, SIBERIA.

The sky-line follows the boundary between the steep fiord wall and the smooth topography of the upland. A spit projecting from the end of the wave-wrought shore cliff protects the more distant part of the wall.

spits, the product of wave action under present conditions. The smoother and older topography is not altogether devoid of steep slopes, but gives an impression of close adjustment between processes of subaerial erosion and the unequal resistances of rock masses. I saw nothing in its profiles and contours to indicate glaciation. The newer and steeper slopes are associated with the troughs containing the bays in such way as to suggest glacial action, but those that we passed near betrayed no smoothing, grooving, or other minor feature of glacial abrasion. The shore walls of Plover Bay are precipitous rock cliffs at top and consist of talus at base, one phase passing into the other in a manner suggesting that the original rock profile was somewhat similar to the one brought about by

partial disintegration. They run straight for long distances. The chief agencies competent to produce such features are faulting and glacial sculpture, and in this case glacial sculpture appears to me the more probable agent, although subsequent weathering seems to have destroyed those minor details of configuration which one naturally seeks as confirmatory evidence.

There are two accessory features which lend support to the hypothesis of glaciation. In the far distance, at the head of the bay, we could see that its trough is connected with two or more land valleys, and it was evident that the valley most nearly in the direct line of prolongation is distinctly U-form in cross-profile and has walls of simple contour. The other feature is a niche, high on the wall of the fiord, having the form of a cirque or hanging valley (fig. 93). In this case I attach little weight to the testimony of the hanging valley, because it has no companion on the long line of cliffs, and therefore may possibly be a simulative form, determined by local peculiarities of rock texture; but the distant valley is distinctively glacial in habit.

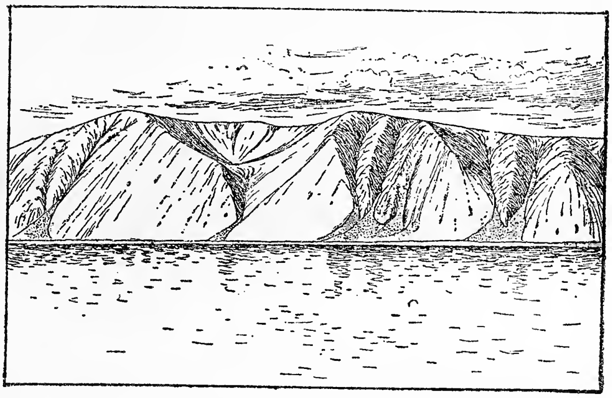


FIG. 93. HANGING VALLEY ON WALL OF PLOVER BAY. Figure 92 gives an oblique view of the same wall.

It seems to me on the whole probable that the fiords of this coast contained Pleistocene glaciers of large size, which extended farther seaward than the general line of the present coast, but that the spaces between the fiords were not covered by ice.

My observations on the coasts of Bering Sea may be summed in the statement that Plover Bay and neighboring Siberian fiords have features indicating local glaciers of considerable magnitude, that evidence of glaciation was seen at no other points, and that certain crags and pinnacles on St. Matthew and St. Paul islands seemed inconsistent with the theory of a continental glacier in the Bering Sea region. My interpretations at the north agree substantially with those of Nordenskiold; at the south with those of Russell.

So far as the Port Clarence region is concerned, what I have said above has become ancient history before reaching the press. A delay of four years between observation and publication is fatal to novelty, if one's theme concerns a region developing under the stimulus of the discovery of gold. Near where we landed on the shore of Port Clarence the town of Bering now stands, and all Seward Peninsula has been explored by the prospector. To aid him the U. S. Geological Survey has sent active parties of geologists and topographers; and as the proof sheets of these pages pass through my hands, I am able to examine contour maps of a large part of the peninsula, and study three comprehensive reports of geologic reconnaissance. These reports are by Brooks, Mendenhall and Collier, and tell of explorations and surveys made in the seasons of 1900 and 1901.[1]

They cover the general question of Pleistocene glaciation in a demonstrative and altogether satisfactory way. The Kigluaik Mountains, between Port Clarence and Cape Nome — mountains with an extreme height of about

[1] A Reconnaissance of the Cape Nome and adjacent Gold Fields of Seward Peninsula, Alaska, in 1900. By Alfred Hulse Brooks. 1901. See pp. 42–53.

A Reconnaissance in the Norton Bay Region, Alaska, in 1900. By Walter Curran Mendenhall. 1901. See p. 208.

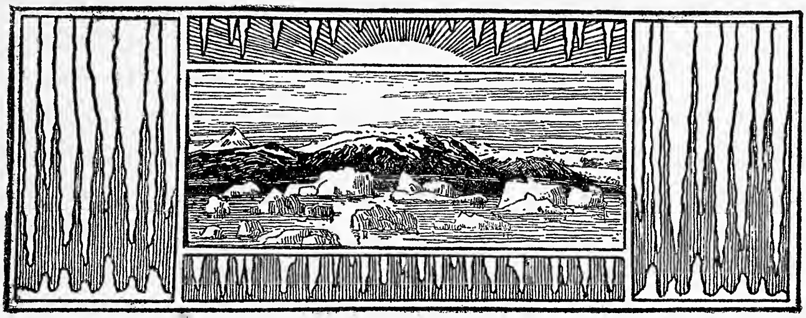
A Reconnaissance of the Northwestern Portion of the Seward Peninsula, Alaska. By Arthur J. Collier. In press. See pp. 24–29 and 34–42.

4,700 feet — nourished in Pleistocene time local glaciers of some magnitude. These are attested by U-troughs, cirques, moraines, and moraine lakes. One of them passed southwestward beyond the foothills of the range, and may have reached the sea. Another approached or reached sea-level at the north. The Bendeleben Mountains, farther inland, also contained glaciers, but too small to push beyond the foothills. Among the York Mountains, which stand between Port Clarence and Cape Prince of Wales, and have an extreme height of about 2,900 feet, were probably small glaciers, but, if so, they were wholly contained in the mountain valleys. Except for these local developments, the surveyed parts of Seward Peninsula — namely, the southern and western parts — were not occupied by Pleistocene ice. Over large areas the mantle of residuary waste lies undisturbed on the rock from which it was derived; and in these areas are angular and slender crags, as well as perched boulders of disintegration, lying in their original positions. Other large areas bear rolled gravels, associated with a series of marine terraces.

One of the marine terraces described by Collier and Brooks was seen by us along the southern base of York Mountains. It is there a conspicuous bench, ending seaward in a steep bluff, and has a height of about 600 feet. According to Collier, its uplift has been unequal, so that the old marine plane is now a warped surface. The fact of warping also accords with my observation, for such parts of the neighboring Siberian coast as I was able to study from the ship seemed altogether free from marine terracing.

An observation of progressive modern change of level was made on St. Matthew Island. A small bay on the east shore, near Glory of Russia Cape, has been cut off from the sea by a series of shore bars. After the first bar

or spit was completed, another was built outside it, and so on to the number of six or more. The one next the sea has a crest considerably above high-tide, at the extreme limit reached by storm waves, and the top of it is covered by drift-wood, to which annual additions are doubtless made. The next bar, lying back of this and parallel to it, is six feet lower. It also is covered by drift-wood, but the wood is decayed, so that no sound logs were found. Two others are successively lower and have no drift-wood, and the innermost are so low as to be covered by the water of the bay. It is evident that each of these ridges of shingle was formed by storm waves at the shore, and we may assume that its crest height was originally as far above high-tide as the crest of the outer ridge is now. The existing differences in height have resulted from the gradual sinking of the land, and a rude indication of the rate of sinking is given by the drift-wood. The inner ridges were made so long ago that the drift-wood they originally bore has rotted away and disappeared. The age of the second ridge has given time for only the partial decay of the timber upon it, and the inference is that the island has sunk to the extent of six feet in a period less than that necessary for the complete destruction of logs through the processes of decay.



CHAPTER III

GENERAL CONSIDERATIONS AS TO GLACIERS

Some of the field observations recorded in the preceding chapters have more than local interest in that they open theoretic questions and lead to suggestions bearing on the general subject of glaciers and their work. Certain of the suggestions have already been noted, as they seemed to belong to the discussion of the associated observations, but others may more appropriately be considered by themselves and have been reserved for the present chapter. The general considerations already set forth refer to an annual cycle in the distal extent of tidal glaciers (p. 22), the production of features of shore topography by waves generated by the calving of icebergs (p. 69), anomalies in the variations of glaciers (p. 106), the origin of pitted plains (p. 54), and the origin and interpretation of hanging valleys (p. 114). The considerations to be presented in the following paragraphs pertain (1) to the broader characters of the surface of a glacier, (2) to the conditions affecting types of glacial sculpture, (3) to the conditions

of wear below sea-level, and (4) to the parallelism of glaciers and rivers.

THE SURFACE OF A GLACIER

Evenness as Compared to Rock Floor. — The parts of glaciers which came under my observation were the lower or distal portions, with surfaces usually less than 1,000 feet above sea-level. In these lower parts the master characters of the surface are a forward slope in the direction of flow and horizontality in the direction normal to the flow, the direction of flow being inferred from the courses of medial moraines.

The configuration of the rock floors beneath the glaciers could not be directly observed, but it was possible to infer their general characters, with high probability, from what could be seen of the rock floors in front of the glaciers. Such rock floors are in all cases abandoned glacier beds, having been covered by the ice not only in Pleistocene times but, in many instances, in historic time also. As a rule these bared portions of the glacier troughs exhibit much irregularity. The fiords vary rapidly in depth; in places they are diversified by islands. The land troughs have hills and hollows; and other hills jut through the glaciers as nunataks. It is therefore believed that the bottoms of the glacier channels have in general considerable inequalities.

These irregularities are only slightly represented in the configuration of the glacier surface. The greater inequalities of the longitudinal profile of the bed are shown by cascades of the glacier, but inequalities of the cross-profile are rarely indicated by visible shapes of the ice, and bosses or hills hundreds (perhaps thousands) of feet high may fail to influence the surface. If the summit of a boss approaches the surface it produces crevasses, but the broader features of the surface contours are not changed.

This leveling of the surface is of course ultimately caused by gravity, and it is immediately brought about by variations in the flow of the ice, the directions and velocities of the flow of different parts being so modified as to permit the ice to pass around and over obstructions without lifting the glacier bodily. The existence of internal variations in direction, being attested by the arrangement of striæ on lands that have been glaciated, is a well-recognized fact, but variations of direction alone are not sufficient to explain the coexistence of an approximately even glacier surface with a very uneven glacier bed. The condition of continuity can not be satisfied without variations of velocity also within the mass. The adjustment of an ice stream to an irregular channel through the formation of differential currents is thus quite analogous to the adjustment observed in water streams, although the greater viscosity of the ice may be assumed to prevent the occurrence of reversed currents or eddies.

Another factor in the leveling of the ice surface is probably connected with ablation, or the process of wasting by melting and evaporation. Portions of the Muir and Hugh Miller glaciers which were demonstrably stagnant, nevertheless exhibited to the general view a conspicuous evenness, and the same remark applies to glacier remnants stranded, like Reid's 'Dying Glacier,' on saddles, or trough summits. These motionless and wasting ice bodies, though not tabular but curved downward toward their edges, were bounded by simple symmetric contours, indicative of equable reduction by the wasting agents and a general interdependence of process for the whole surface.

Lateral Cliff. — Coexistent with the general tendency toward evenness are several kinds of unevenness, each determined by some evident special condition. Wherever the side of an ice stream was observed adjacent to a rock wall, it was found to present a cliff toward the rock, the

ice cliff and rock wall constituting the sides of a narrow valley or fosse, usually 50 to 100 feet deep. A stream of water sometimes followed the valley. This feature, familiar in all glacier districts, has been explained as due to the heat acquired by the rock through insolation and then conveyed by radiation to the adjacent ice; and the stream of water, when present, would help to account for the valley, for so much of its volume as came from the sun-heated rock would be warmer than the water of ablation and have some power to melt ice.

Crevasse Cycle.—Wherever the work of the sun is not complicated by the presence of rock débris, the inequalities initiated by crevassing are carried by ablation through a regular cycle of change, ending in their complete re-

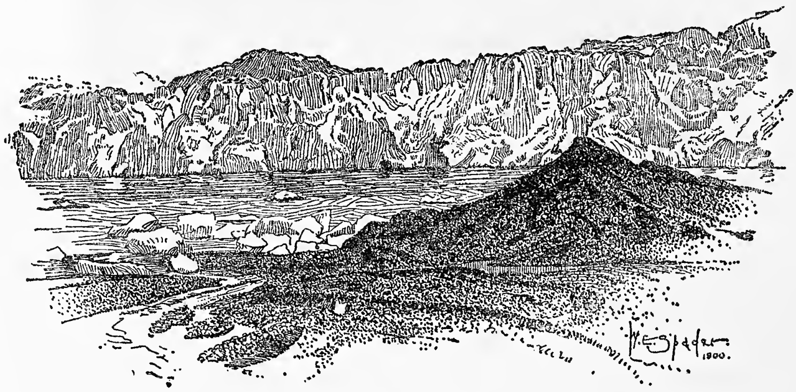


FIG. 94. DOWNWARD LIMIT OF CREVASSES IN MUIR GLACIER.
The lower part of the ice is undivided; the upper is split into slabs and columns. The dark hill in foreground is of ice with a cover of gravel, a remnant of the retreating glacier.

moval. In the crevassing which begins abruptly at the head of a cascade, the cracks divide the ice into flat-topped, elongated blocks, usually tapering toward the ends and more or less connected at the surface by slender masses analogous to the slivers of half-broken timber. Whatever the distance downward to which the cracks may originally extend, the resulting permanent crevasses have

only moderate depth, the ice being welded into a practically continuous mass beneath. Wherever a crevassed tract was exhibited in section in a tidal cliff, the crevasses were seen to terminate uniformly along a definite zone, which was usually nearer the top of the cliff than its base. The depth of this zone was estimated in different instances at from 50 to 125 feet, but this did not represent the full original depth of the crevasses, as something had in every case been lost by ablation (fig. 94).

As soon as the cracks are opened, melting begins on

FIG. 95. CREVASSES AND SERACS, MUIR GLACIER.

their faces, the rate being greatest above, and the flat tops of the ice blocks, the *seracs* of alpinists (fig. 95), are converted into roof-like crests and pinnacles. In this condition the surface is nearly or quite impassable (fig. 96). With continuance of ablation the height of the seracs is reduced, their slopes become less steep, and many connecting cross ridges become available to the wayfarer, so that with the exercise of care and patience one can make his way safely in any direction. Figure 97 shows a characteristic field of this sort, crossed by some of our party on their way to the great nunatak of the Columbia Glacier. A continuance of the same reduction by ablation eventually obliterates the ice waves alto-

gether, leaving a plain surface over which progress is absolutely unimpeded (fig. 98).

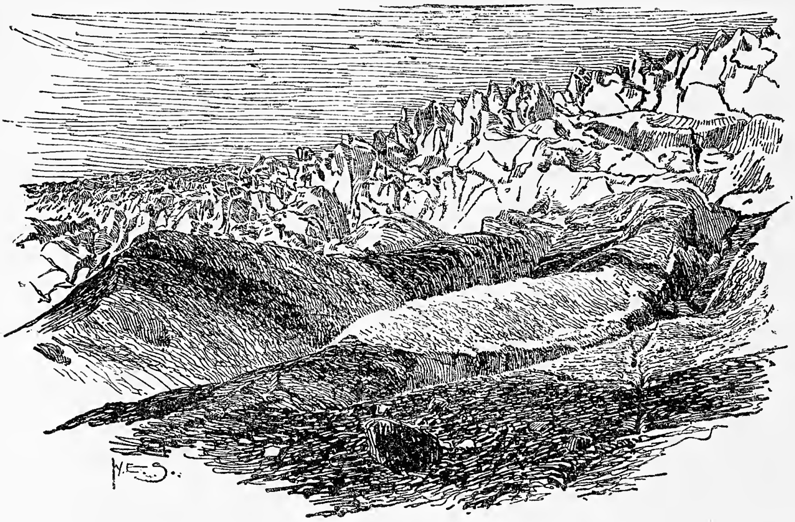


FIG. 96. PINNACLES ON COLUMBIA GLACIER.

Thus the cycle of ice degradation by ablation is strictly analogous to the cycle of land degradation by erosion; an original plain is rapidly converted into a region of highly accidented topography, which slowly returns to the plain condition through the removal of its prominences. If the cycle is interrupted by the formation of a new system of crevasses, the analogy still holds,

FIG. 97. BACK OF COLUMBIA GLACIER.
Illustrating gradual smoothing of surface.

for the features of the new cycle thus instituted at first combine with those of the old and eventually supplant them.

As my excursions on glaciers were all short, it happened that I never saw a complete illustration of the ablation cycle on one glacier, but such examples should be readily discoverable. Where the even bed of a glacier increases its grade, where it is interrupted by a step, producing a cascade, or where the overriding of a submerged peak produces breaking strains in the upper part of the ice stream, the smooth ice plain above, the prismoidal blocks, the acute peaks, the gradually subsiding waves, and the final ice plain should appear in regular sequence, substantially as represented in figure 99.

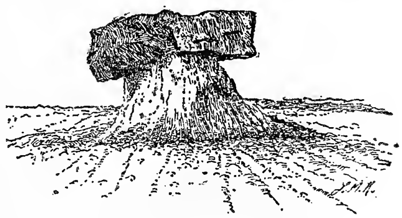


FIG. 98. LEVEL TRACT ON MUIR GLACIER.

The rock retards the melting of the ice on which it rests, and thus preserves a pedestal.

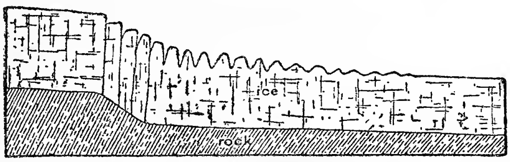


FIG. 99. IDEAL PROFILE AND SECTION OF A GLACIER.

Illustrating the formation and obliteration of crevasses and seracs.

An exceptional condition was observed on the tongue of the Columbia Glacier which flows into the western embayment of its valley. A plain surface was there interrupted by an extensive plexus of crevasses, which were filled to the brim with water and snow (fig. 100). The normal cycle appeared to be varied in this case by a lack of drainage, surface ablation progressing only where the air had access, and truncating the seracs down to the waterline. It is conceivable that under such conditions a set of crevasses originating from horizontal stresses may pro-

duce no crests and pinnacles, but remain as mere interruptions of a general plain surface until obliterated by progressive ablation.

This exceptional condition draws attention to the fact that crevasse systems are normally underdrained. Looking into crevasses on a warm day, one may sometimes see the water of ablation in slender rills disappearing down tunnels or shafts in the compact blue ice below — to be gathered doubtless in englacial or subglacial streams, and eventually escape at the end of the glacier.

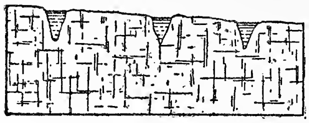


FIG. 100. IDEAL SECTION OF WATER-FILLED CREVASSES AND TRUNCATED SERACS.

Where the ice carries a heavy back-load of drift the normal crevasse cycle is greatly modified (fig. 101) and its completion indefinitely postponed. As already mentioned in connection with the Hidden Glacier, the drift falls into the crevasses and gathers at their bottoms. As the intervening ice blocks acquire acute crests the greater part of the drift rolls and slides from them, and they retain only enough to darken the surface. Under the familiar law that a sprinkling or thin cover of drift promotes melting, while a heavy mantle retards it, the pinnacles are rapidly reduced, and their sites are eventually depressed below the drift masses accumulated in the crevasses. The original asperities made by the crevasses have now been destroyed, but a secondary system has been evolved, which tends in similar manner to produce a tertiary system, and so on indefinitely. Wherever we found a broad

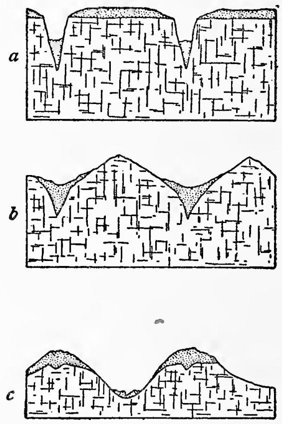


FIG. 101. INFLUENCE OF DRIFT ON SURFACE CHARACTER OF GLACIER.

Crevasses formed in drift-covered ice (*a*) accumulate the drift (*b*), and eventually become the sites of hills (*c*).

tract of ice heavily loaded with drift, its surface was made up of hummocks and hollows, varied here and there by cliffs of black ice, down which pebbles and boulders occasionally rolled in shifting their position from hill to hollow. These irregularities, involving, as they do, inequality in the distribution of the drift on the surface of the ice, help to account for the irregularity observed in terminal moraines.

GLACIAL SCULPTURE

The work of rock sculpture accomplished by the middle and lower parts of a glacier is performed chiefly by the processes of abrasion and plucking. In abrasion, fragments of rock held in the under part of the ice, being dragged over the fixed rock of the glacier bed, file away and reduce it. In plucking, blocks of bed-rock, being partly surrounded by the ice, are forced from their bearings and rolled or slidden forward. If the plucked blocks have originally stood as projections, they may be broken away, even if quite firm and flawless; otherwise it is probable that they can be removed only if originally separated by joints or other structural partings. The waste resulting from abrasion is clay and sand; plucking yields boulders.

One of the chief factors on which the rate of abrasion depends is the velocity of the moving ice. If the bed-rock surface is uneven, the ice does not flow over all parts of it at the same rate, but moves slower in the hollows and faster across the prominences. This difference results partly from the condition of continuity, which demands higher average speed where the cross-section is less, and partly from the tendency of parts embayed in hollows to lag behind the general mass. The prominences are therefore abraded more rapidly than the adjacent hollows, and the profile is thus reduced to simple forms.

Another factor on which rate of abrasion depends is

pressure; the abrasion is more rapid as the pressure of the glacier against the bed-rock is greater.[1] The resistance which the moving ice, through its viscosity,[2] opposes to change of form, causes it to press unequally on different parts of an uneven bed, and to abrade most rapidly those parts whose prominence compels the ice to change its direction. Thus in a second way there is a tendency to reduce the profile of the bed to simple forms.

The amount of resistance developed by viscosity depends on the rate of deformation; more force is necessary to deflect the ice quickly than to deflect it slowly. The parts of the bed which cause the most abrupt turns are therefore subjected to greatest pressure and to greatest wear, with the result that the profiles of the bed eventually become curves of large radius, adjusted to slow bending of the moving ice.

If the general motion of the ice is very slow, the resistance developed by viscosity is small and the resulting sculpture curves have comparatively small radius. If the ice moves rapidly, the sculpture curves have large radius.

[1] There are two theoretic limits to the law that abrasion increases with pressure. It has been argued by N. S. Shaler that because the melting temperature of ice is lowered by pressure, the basal part of a thick glacier must consist of water instead of ice (Outlines of the Earth's History, pages 237–239, 1898); and such 'pressure-molten' water would manifestly be powerless to grind rock waste against the rock bed. G. F. Becker has suggested to me in conversation that where the pressure is great there also the elastic limit of the ice is far exceeded and the ice should be expected to flow about rock fragments so as to incorporate them in the glacier and reduce or destroy their effectiveness as tools of abrasion. These considerations are not included in the above analysis because, while I do not see my way to their satisfactory discussion, I fail to perceive that they help to explain the phenomena of ice erosion as seen in Alaska. Whatever their influence may be, it has not prevented exceptionally great erosion in places where the Pleistocene ice was exceptionally deep.

[2] In untechnical usage the word *viscosity* is ambiguous, being applied to a property of liquids opposed to mobility and to a property of solids opposed to rigidity. In the present paper it has the technical meaning given by the physicist, and is the property of fluids and solids in virtue of which internal differential movement, or shear, consumes time. The greater the viscosity the slower the yielding to a given shearing force.

The tendency toward curves of large radius is more effective where the material of the bed is easily worn than where it is obdurate.

A third factor affecting rate of abrasion is the material abraded. Some materials yield more easily than others and are worn more rapidly. Where the material of the glacier bed is heterogeneous, including both yielding and obdurate rocks, there is a tendency to hollow out the yielding rocks and leave the obdurate masses prominent. This tendency is opposed by those arising from the viscosity of the ice, and the type of the resulting sculpture in each individual case is a compromise. It is thought that the relative importance of viscosity is greater with swift-moving ice than with slow-moving ice.

A fourth factor is found in the quality and quantity of the abrasive material, the rock particles set in the base of the ice. The particles picked up from shale would not be effective in grinding quartzite, but particles from quartzite would act vigorously on most other rocks. The abrasive action of pure ice is probably nil. The influence of this factor is not easily formulated, but there can be no question that it qualifies the influence of other factors in important ways.

The sculpture wrought by plucking differs notably from that due to abrasion. The plucking of a block of rock removes a projection and leaves a hollow. A surface which has been reduced chiefly by plucking abounds in salient and reentrant angles, and would be called hackly if its pattern were smaller. Usually its salients, and often its reentrants, are rounded by subsequent abrasion, producing a topography to which Saussure's title of *moutonnée* is peculiarly applicable.

The conditions which locally determine plucking rather than abrasion are not clear to me. Evidence of plucking is seen more frequently on hard rocks than on soft. The

clearest examples are on salient masses, but this may be merely a question of exposure, for the finest illustrations of abrasive sculpture are also on salients. Where a heterogeneous rock bed acquires an uneven surface by abrasion, the prominences of obdurate rock would be specially exposed to plucking, and it is easy to understand that plucking may be combined with abrasion in the reduction of such a tract.

The unevenness produced by plucking is a minor feature of the sculpture topography. When greater features are considered it is evident that plucking as well as abrasion is more active on salient than on reentrant profiles, for however hackly an ice-worn hill may be in detail, its general profile and contours have the same sweeping curves which characterize the products of abrasion.

The preceding discussion, which for brevity has been given somewhat deductive form, is largely based on field observation, being the result of an endeavor to understand the varied phenomena of sculpture observed in Alaska. In a region where the evidence of great glacial erosion is overwhelming, where multitudinous hanging valleys, the general obliteration of spurs from the sides of U-valleys, and the dominant and thorough rounding of crests and corners of hills and small mountains, testify to an enormous amount of glacial degradation, it was a matter of surprise to find the reduction of the surface to smooth-sweeping curves a somewhat rare phenomenon. By far the greater number of well-exposed glaciated areas, even where the degradation has been profound, abound in low embossments and in more or less angular groins or reentrant spaces showing little trace of abrasive action. These surface characters presented themselves as facts requiring explanation; and I have come to regard them as indications of the great importance of plucking in the work of glacial erosion.

EXPLANATION OF PLATE XVIII

Glaciated Rocks

Upper Figure.—A portion of the east wall of the valley containing Muir Glacier, at a point nearly opposite the end of the glacier in 1899. The conspicuous polished surfaces are 200 to 300 feet above tide-level, and were probably covered by ice a century ago. The direction of movement was from left to right. See page 207.

The axis of the camera was elevated. Photographed by G. K. Gilbert, June 9, 1899. Negative no. 243, United States Geological Survey.

Lower Figure. — The foreground shows an ice-worn prominence of the east wall of Muir Valley, just south of the Dirt Glacier. It is viewed from the up-stream side. Its altitude is about 550 feet. It was probably covered by ice a century ago. See page 208.

The distance shows Muir Inlet and its western wall, with a foreland of water-laid gravels — an ancient moraine delta.

Photographed by G. K. Gilbert, June 9, 1899. Negative no. 269, United States Geological Survey.

GLACIATED ROCKS

HELIOTYPE CO., BOSTON.

The importance of plucking may also be inferred, as in fact it has been by Dana, from the abundance of boulders in the moraines of an ice-sheet. In the waste deposited by an alpine glacier it is not easy to discriminate plucked boulders from the boulders which have fallen to the ice from adjacent rock slopes and been carried forward as back-load, but the waste carried to the edge of a great ice-sheet like the Laurentide has all been picked up as well as transported by the ice. A portion of such a body of waste must be referred to the mantle of residuary and alluvial débris found initially on the land by the expanding ice mass, and this portion of course includes a contingent of boulders; but there is no reason to regard this factor as of great importance. It is probably much more than offset by the destruction of boulders in the glacial mill, for in the making of the rock flour which constitutes the body of glacial till, the abrasion of the coarser waste carried by the bottom ice may approach, or even exceed, the abrasion of the rock floor. While these various factors do not admit of definite valuation, I think it fair to say that the ratio of boulders, on the one hand, to clay and sand, on the other, in the waste deposits as a whole, is something less than the ratio of plucking to abrasion in the erosive work of such an ice-sheet as the Laurentide.

The study of this subject made such slow progress in the field that opportunities for good photographic illustration were not improved. The views reproduced in plate XVIII were taken to show abrasive work, and illustrate plucking only incidentally. The upper view looks up the wall of Muir Inlet. It shows stratified rock, with a boss of more massive, possibly plutonic, rock beyond. A century ago all the stratified rock was covered by Muir Glacier. At the left near the sky-line the strata are seen to be obliquely truncated, and the plane or nappe of trun-

cation can be traced across the view. It really includes the foreground, at least down to the mantle of moraine; and it is part of the wall of the glacier trough, wrought by the ice into curves of large radius. But the detail of this erosion plane, shown in the center of the field, is distinctly hackly, as though (and probably because) the degradation of the stratified rock was accomplished largely by the breaking away of blocks. The prominent angles and edges of strata are abraded and highly polished on their stoss sides, but their lee facets are unworn.

The lower view shows the stoss side of a granite knob, also near Muir Glacier. Here the indications of abrasion are most conspicuous, but a groin crossing the foreground, and a niche at the right, are probably remnants of scars made by plucking.

The rock areas best showing the character of the sculpture due to plucking are in the barren regions about the glaciers, and these were often included in our views of glaciers; but the photographic methods employed to show details of the white ice do not secure the details of dark rocks. The peculiar embossment topography is merely suggested in some cases by the pattern which results from the preservation of snow in concavities of the surface. See the mountain spur beyond Reid Glacier in figure 14 and the hill at the left of Hugh Miller Glacier in plate III. Similar patterns appear on both sides of Serpentine Glacier, in the photogravure at page 124 of volume I.

Figure 102 contrasts several types of sculpture. A tract bordering the water of the fiord at the right shows elaborate fluting on a grand scale, the abrasive work of a powerful, and doubtless fast-moving, ice stream, flowing from left to right through the fiord. The material here sculptured is argillaceous slate, similar to that at Kadiak (figs. 86 and 87). The spurs beyond are partly of more obdurate material, including schists and granitoid rocks;

they were sculptured chiefly by currents approaching the fiord from the right; and plucking was an important factor of the process. The peaks against the sky were above the Pleistocene ice.

In the last example the unevenness in the region of extensive plucking is partly due to the varying resistance of heterogeneous bed-rock. This factor finds strong expression in the forelands and low islets at New Metlakatla, Sitka, and Kadiak, where peneplains well reduced toward base-level, and therefore presumptively of nearly even surface, were much roughened by a moderate amount of glacial degradation (see figs. 64, 65 and 86, and pl. XVII).

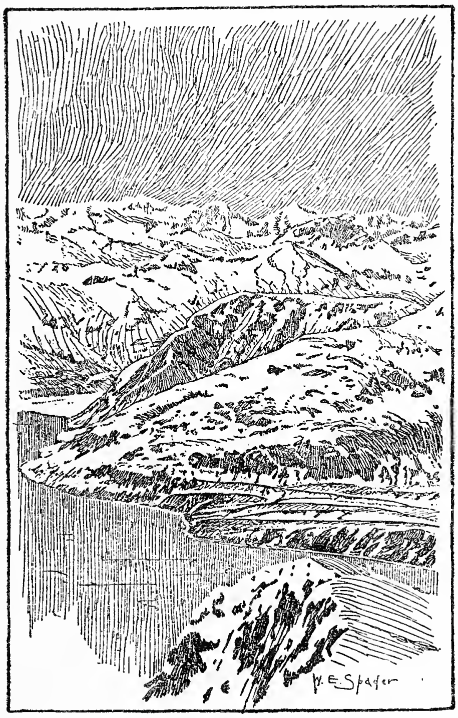


FIG. 102. ICE SCULPTURE IN RUSSELL FIORD.

It is also strongly expressed on the slopes of Unalaska Island about Unalaska Bay. There is a general lumpiness of the surface which would throw doubt on the theory of extensive Pleistocene glaciation were the theory not strongly supported by the conspicuous glacial sculpture of other parts of the island. Except where exposed in sea cliffs, the rocks are largely covered by a tundra mat, and this leaves room for doubt as to the steeper slopes, where many of the knobs may be landslips; but on the gentler slopes the knobs are clearly obdurate elements of the heterogeneous volcanic mass, rendered prominent by

differential erosion. A strip of lowland between Dutch Harbor and Iliuliuk is so hummocky and so set with lakelets as to remind one of a terminal moraine of the Laurentide ice-sheet, and I half expected to find it a heap of glacial waste; but every discovered break in its turfy mantle revealed volcanic rocks *in situ*, and I was forced to regard its undulations as products of sculpture.

PRESSURE AND EROSIVE POWER OF TIDAL GLACIERS

The discussion, in the last chapter, of the fiords of the Alexander Archipelago assumes (page 163) that a tidal glacier is partly supported by the sea, so that the full weight of the ice does not press on the rock floor, and the glacier's power to erode is correspondingly diminished. This assumption has been often made, and is usually given quantitative form. The sea is said to sustain a portion of the glacier equal in weight to the body of water displaced by the ice, and correspondingly to diminish the pressure of the glacier on its bed.

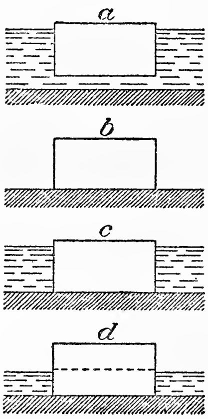


FIG. 103. DIAGRAMS ILLUSTRATING FLOTATION THEORY OF TIDAL GLACIERS.

When the subject is approached in a certain way this view seems altogether plausible. In figure 103, *a* represents in section a sea 2,000 feet deep with a flat bottom. In the sea floats an iceberg of which the sides are vertical and the top and bottom are horizontal planes. Its thickness is 1,600 feet, and the submerged part measures 1,400 feet, the densities of the ice and the water having the ratio of 7 to 8. The water sustains the entire weight of the ice. Now conceive the water of the sea to be drained away. The block of ice sinks to the bottom (*b*) and is wholly supported by it. Again, conceive the water of the sea to be only partly withdrawn, the depth being reduced from

2,000 feet to 1,400 feet (*c*). This is equivalent, so far as the block of ice is concerned, to raising the sea bottom from its position in *a* until it touches the base of the ice-berg. The ice is not lifted by the sea bottom; it still projects into the air just 200 feet; it is still supported by the water, and though touching the sea bottom does not press on it. Finally, conceive the water drawn down until its depth is but 700 feet (*d*). This depth of water is just able to float a berg 800 feet thick. Therefore 800 feet of ice, or one-half the thickness of the block, are now supported by the water, and the remaining 800 feet by the sea bottom.

Let us now approach the subject in a different way. Begin with a block of ice of the same dimensions as before, resting on a horizontal bed, with which it is everywhere in contact (fig. 104, *a*). The pressure on each square inch of the bed equals the weight of the column of ice above it — about 640 pounds. Now introduce sea water about the ice until it has a depth of, say, 700 feet (*b*). The water presses horizontally against the vertical faces (as indicated by the arrows), but, as there is no vertical component to a horizontal force, the water pressure neither lifts the ice block nor pushes it down. The block continues to rest on the bed, exerting still a downward pressure of 640 pounds per square inch of base. This line of reasoning seems quite as plausible as the other, but the result is different.

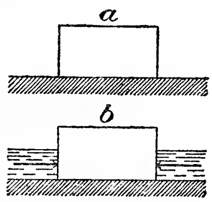


FIG. 104. DIAGRAMS ILLUSTRATING NON-FLOTATION THEORY OF TIDAL GLACIERS.

A little consideration discovers the cause of the discrepancy. In the first analysis it is tacitly assumed that the water exerts its pressure not only on the sides of the ice block but on its base, and this whether the block floats free or touches the sea bed. In the second analysis it is

tacitly assumed that the contact of the ice with the bed excludes the water. In order to determine which analysis is applicable to the case of the tidal glacier, it is necessary to consider whether the nature of the contact between the glacier and its bed is or is not such as to exclude the sea water and its pressure.

It was suggested by my colleague G. F. Becker that a laboratory test might be applied to one of the principles appealed to in the second of the two analyses — the principle that a solid rectangular block immersed in a liquid is not buoyed up by the liquid provided its base is in complete contact with the bed on which the liquid rests; and at his request two pertinent experiments were made by A. L. Day in the physical laboratory of the U. S. Geological Survey. In the first experiment a small slab of plate glass was cemented to the bottom of a glass vessel (fig. 105), for the purpose of giving an accurately plane surface, and the vessel was then partly filled with mercury. A second piece of plate glass was immersed in the mercury and pushed down until one of its faces came into contact with the face of the fixed slab. As the density of mercury is about five times that of glass, some force was needed to immerse the block of glass, but as soon as contact had been secured with the slab below, the block remained at the bottom. Not only did it show no tendency to rise, but force was necessary to detach it. As both glass surfaces had been carefully cleaned, there could be no cementation; the phenomenon was one of hydrostatic pressure, conditioned by the contact relations of glass with mercury.

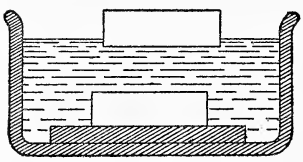


FIG. 105. CONTACT PHENOMENA OF GLASS AND MERCURY.

A block of glass rests on the bottom; a similar block floats at the surface.

In the second experiment water was substituted for

mercury; and, as glass is heavier than water, the glass block was replaced by a block of cork, to the bottom of which a thin plate of glass was cemented. When the cork was pushed down through the water and its glass face squeezed against the slab of glass at the bottom, it was found to adhere, but not permanently. The pressure applied did not force all the water from between the glass faces, and the remaining water film gradually thickened, until, in a few seconds or a few minutes, the cork was freed and rose to the surface.

As regards conditions, the only essential difference between the two experiments was in the liquids employed, and the properties of the liquids which determined the diverse results were the relations of internal to external molecular forces. Because the cohesive force of water is less strong than its force of adhesion to glass, water 'wets' a glass surface; it is able to spread and interpose itself as a film between two glass surfaces pressed tightly together; and when thus interposed it can not be forced out by pressure (at least, by such pressure as is involved in the problem of the tidal glacier). Because the cohesion of mercury is stronger than its adhesion to glass, it does not wet glass; and it does not tend to insinuate itself between closely approximated glass plates, but tends rather to withdraw from the interspace.

These experiments indicate that the ability of the sea to penetrate, and communicate its pressure, along the contact surfaces of a tidal glacier and its bed, may depend on the cohesive force of water, as compared with its adhesive force in relation to ice and rock. It is a familiar fact that water wets both ice and rock; and the problem of the glacier is therefore better represented by the second of Day's experiments than by the first.

Another factor of the problem should now be considered, the temperature of the bottom ice and adjacent rock;

for if these fall below the freezing temperature, a film of water can not exist between them. This is a subject which has received considerable attention, and although direct observation is impossible, there seems a good foundation for inference. By the aid of crevasses and borings it has been found that the upper ice (outside the névé region) has at all times a temperature of almost exactly 32°, seasonal and diurnal variation being confined to a very thin surface layer. The upper ice therefore has no cooling effect on the bottom ice. On the other hand, the bottom ice receives heat in three ways: Heat comes to it by conduction from the interior of the earth; heat is developed by the friction of ice and waste on the bed-rock; and the internal work of the flow of the ice develops heat, of which a part is conducted downward. The bottom ice therefore maintains a temperature of 32° (more precisely, the freezing temperature corresponding to the pressure), and the adjacent rock is slightly warmer. There is a continual, though very slow, melting of the basal ice, and a film of water is maintained between it and the rock. It is probable that the streams of water which flow from glaciers all through the winter are supplied chiefly by basal melting; and we may further suppose that the tunnels through which those streams flow are connected with the thin water film by a graduated and ramifying system of minor passages. The ways which serve for the escape of the product of basal melting serve also, in the case of tidal glaciers, for the communication of the hydrostatic pressure of the sea water.

Statically considered, the film of water under the glacier is subject to a group of forces in equilibrium. The weight of the glacier presses on it and tends to expel it. This is resisted by the molecular forces associated with the contact faces of the film, and by the hydrostatic pressure of the sea water outside. As the film is added to by

melting, and as the added water must escape by flow, there is also a dynamic factor, the viscous resistance to flow. These forces conjointly determine the thickness of the film. The film is thicker as the ice column is less, as the sea-water column is greater, and as the melting is more rapid. It is always very thin.

We may now advantageously return to the question of the mode of support of the tidal glacier. Referring to the diagram (fig. 106), it is evident that the ice receives no support from the pressure of the sea water against its frontal cliff. It rests wholly on the film of water beneath it, and its pressure is communicated by the film, without loss, to the rock beneath. The film is not a mere conduit, communicating the static pressure of the sea water. If it were, the ice would not be supported, because that pressure is less than the downward pressure of the ice. In virtue of the molecular forces brought into play along the contact planes, the film has some of the properties of a solid. It is, in some sense, an elastic spring or cushion interposed between the ice and the rock. It performs its function of transmitting the pressure of the glacier to the rock bed quite independently of the presence of the sea. The pressure of the sea water modifies the infinitesimal thickness of the film, but does not prevent the rock bed from supporting (through the mediation of the film) the whole weight of the glacier.

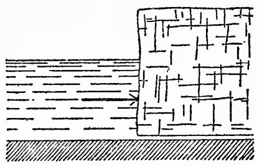


FIG. 106. IDEAL SECTION OF TIDAL GLACIER. Showing relation of the sea to the subglacial water-film. The thickness of the film is enormously exaggerated.

The last statement is subject to a single qualification. Wherever the feeble flow of water from basal melting maintains passages of more than capillary size, the molecular forces locally cease to dominate, and the hydrostatic pressure of the sea water contributes support to the glacier. To this extent, which must always be relatively

very small, the pressure of a tidal glacier on its bed is diminished by the sea.

It thus appears that there is no important difference, as respects pressure on the rock bed, between a glacier resting on the land and one which is partly bathed by the water of a fiord; and, so far as glacial erosion is conditioned by pressure, the presence of the sea does not diminish the efficiency of the glacier. It is possible, however, that the rate of erosion is affected by changes in the thickness of the capillary film of water. In the familiar case of the grindstone, the application of water modifies abrasion in two ways: It acts as a lubricant to diminish friction and reduce the efficiency of the stone; and it acts as a carrier to remove the product of abrasion, prevent clogging, and thus enhance the efficiency. The subglacial film doubtless has both these functions, and both should be affected by its thickness; but as the two are antagonistic in relation to abrasion, it is not at once evident whether a thickening of the film should increase or diminish the erosive work of the glacier.

It seems furthermore possible that the influence of film thickness on abrasion may not be the same for waste particles of all sizes. It may be important with reference to the finest rock flour, where the diameters are of the same order of magnitude as the depth of the film, and quite unimportant with reference to the work of sand and still coarser waste. And if we turn from abrasion to plucking, we seem to pass altogether out of the field of influence of the subglacial film.

While it is not altogether easy to picture the combination of molar and molecular forces associated with the subglacial film, and while it is still more difficult to analyze the effect of variation in that film on so complicated a process as glacial erosion, I am nevertheless confident that the influence of the sea in diminishing the pressure of a

tidal glacier has been greatly overrated, and I discredit the supposed power of sea pressure to make important reduction of a glacier's efficiency for erosion.

The preceding pages were submitted in manuscript to several friends competent to consider questions in molecular physics. Some of them think the ability of the subglacial film to resist expulsion has been overestimated, and especially that the film should not be assumed to exist between the bed-rock and the abrading angles of rock particles held in the ice. If it be true that abrading particles are in absolute contact with the bed, and if it be further true that there is no film between the same particles and the partly enveloping ice, then parts of the glacier (regarded as a body of ice and fragmental rock) are *directly* supported by the bed. However important the distinction may be with reference to a complete theory of glacial abrasion, it seems to have little bearing on the question of pressure as here considered. We may conceive the whole glacier to consist of infinitesimal vertical columns, some terminating on the bed and supported by it, others resting directly on a capillary film of water and thus indirectly supported by the bed, and yet others terminating on a water stratum of supercapillary depth. The last are sustained in part only by the hydrostatic pressure communicated by the water stratum, and are otherwise upheld directly by their coherent neighbors of the first and second groups, and through them, indirectly, by the bed.

It is a corollary to the general conclusion of this section that the existence of a fiord — that is, of a glacial trough partly occupied by an arm of the sea — is not demonstrative of a relatively low base-level at the time of its excavation. In the regions of the Alexander Archipelago and Prince William Sound there is independent reason to think the base-level was relatively low when the glaciers

were largest, but the case is not strengthened by the presence of the sea in the glacier channels.

RIVERS OF ICE AND OF WATER

The resemblance which glaciers of the alpine type bear to streams of water, has impressed all observers, and it includes so many details of form and work that the phrase 'river of ice' seems more than a mere figure of speech. The fact that resemblances arrest attention, of course implies that there are also differences; the contrast between the two materials, ice and water, is so extreme that correspondences in their behavior are unexpected and therefore striking. If we disregard this fundamental difference in material and restrict attention to other causes controlling the phenomena, then we may say that some of the resemblances between glaciers and rivers are of the nature of homologies, in that the causes of the corresponding features are like, and other resemblances are of the nature of analogies, in that the causes are unlike. Before attempting a classification of resemblances on these lines, I shall enumerate the features of alpine glaciers which have been regarded, or which seem worthy of regard, as corresponding to similar features of rivers.

Resemblances. — (1) Upland precipitation is gathered into streams which flow down the slopes. (2) As they flow they meet and join together, forming greater streams, which follow the main valleys or gorges. (3) Sometimes a stream parts against a prominence and reunites beyond it, thus surrounding an island (nunatak); (4) sometimes the parted members proceed independently, as distributaries. (5) All parts of the stream are subject to gain and loss of material. In an upper division gain is in excess; in a lower division, loss. In complete examples the maximum volume is in mid-course, and the stream ends distally by complete dissipation. (6) If the stream

reaches the sea it is cut off, and its history of volume-change ends abruptly.

The velocity of flow is greater (7) in the middle of the stream than at the sides, (8) at the top than at the bottom, (9) on the outer side of a bend than on the inner, (10) where the channel is narrow than where it is broad, (11) where the grade is high than where it is low, (12) in a large stream than in a small.

(13) The surface of the stream, considered as to its major features, is smoother than the channel bed. (14) It is exceptionally high on the upstream side of an island, and exceptionally low on the downstream side. (15) It is roughened in detail by concealed prominences of the bottom, especially where the stream is shallow. (16) The surface descends normally in the direction of flow, but exceptionally, and for short distances, ascends.

(17) The stream erodes its bed and the walls of its channel. (18) The chief tools of erosion are rock fragments carried by the stream. (19) The greater the velocity of the stream the more rapid the erosion (except, perhaps, in cirques). (20) The stream shapes its channel, making the width several times greater than the depth. (21) The fully adjusted channel is broader in yielding material than in obdurate; but has uniform width in uniform material. (22) The contours of the adjusted channel are smooth curves of large radius. (23) The adjusted channels of large streams are broader and deeper than those of small streams. Where a large stream is joined by a small tributary and the surfaces of the two have the same level, the bed of the large stream lies lower than that of the small. (24) The erosion of the channel in gorges saps the cliff walls, causing coarse waste to fall to the stream. (25) The waste from erosion and sapping is carried forward by the stream and eventually deposited.

(26) Where a heavily loaded stream issues from a moun-

tain gorge to an open valley, it sometimes deposits waste at the sides and beneath until it comes to flow in a walled causeway, or raised trough, of its own construction. It may then overflow a wall of the trough and assume a new course.[1]

Differences. — The features of difference are equally noteworthy. The speed of the glacier is very much slower than that of the river, being better expressed in feet per year than in feet per second. The rates of waxing and waning are correspondingly slow. A river flood is propagated downstream by the actual transfer of the water added about the upper course; a glacier flood is believed to be propagated downstream as a wave traveling more rapidly than the ice. The depth and width of a glacier are much larger, in relation to length, than those of a river. The threads of flow in a glacier run nearly parallel; in a river they weave freely in and out. That which falls to the back of a glacier, though much denser than the ice, does not sink to the bottom, but is carried forward as a back-load; only light materials float on a river. Most of the waste embedded in a glacier is moved along continuously; most of the waste constituting the load of a river is transported intermittently, being repeatedly picked up and laid down.

Homologies and Analogies.—The gathering of ice into streams and its downward flow are caused by gravity, just as in the case of water. Most of the inequalities of velocity are determined by gravity in conjunction with the friction of the ice on the channel and the resistance of ice to internal shear; and the processes are essentially the same as with water. But the greater velocity on the outside of a bend involves an analogy only. The bending stream of ice distributes the velocities of its elements in such

[1] I. C. Russell. Eighth Ann. Rept. U. S. Geol. Survey, Part 1, pp. 337–342, 360–366, 1889.

way that the total work of channel friction and internal shear is a minimum, and that distribution throws the locus of maximum velocity to the outer side of the middle of the stream, but the general relations of the parts of the stream are not changed. The preservation of the general relations is clearly shown by medial moraines, which map out surficial lines of flow. In the bending river, momentum is the controlling factor. Those fillets of the stream which above the bend moved fastest are thrown to the outer side of the curve, and the slower-moving fillets are crowded to the inner side. Usually the upper water moves to the outside of the bend and the lower water to the inside, so that there is a torsion of the body of water as a whole.

The correspondences connected with gain and loss of material are close, and the parallelism can be traced through many details, but the processes are so different that the similarities of result can not be classed as homologies. Alimentation of the glacier is primarily through snowfall, secondarily through rainfall, and there is storage in snow banks that subsequently descend as avalanches. Alimentation of the river is primarily through rainfall, secondarily through the melting of snow and ice, and there is storage in ground water that slowly issues in springs. Dissipation of the glacier is chiefly by melting and secondarily by evaporation. Dissipation of the river is wholly by evaporation, but part of its evaporation is preceded by absorption by the ground.

The general evenness of the stream surface is determined in each case by gravity, and so is its descent in the direction of flow; but the exceptional ascent in the direction of flow has diverse causes. Where the passage of an ice stream over an embossment of its bed is expressed by a local rising of its surface, the imperfect adjustment of the surface is a result of viscosity; the upward slope of water under similar circumstances is a result of impetus

or momentum. So, too, the roughening of the glacier surface where the flow is disturbed, by breaking into seracs and pinnacles, is analogous to, rather than homologous with, the breaking of a river surface into waves. Viscosity causes the rupture of the ice, momentum the undulation of the water. The deflection of the viscous ice produces stresses and strains, some of which are tensile; in the depths of the stream the tensile stresses are balanced by compressive stresses due to the weight of overlying ice, but higher up the ice is overstrained and ruptured. When the swift-flowing water rises over an obstruction its momentum causes a portion to shoot above the normal level, and thus starts an undulation.

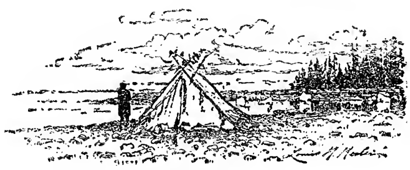
The causes of the relation of channel depth to channel width are not sufficiently understood in the case of glaciers to warrant a comparison with rivers. The disparity of channel depth at the mouth of a small, fully-adjusted tributary is in each case a phenomenon of base-level control. The surface level of the tributary is determined by the main stream, and if the tributary at any time erodes its channel rapidly, its stream becomes deeper, its velocity less, its power to erode less, and thus the tendency to deepen is limited. The resemblance of glaciers to rivers in this respect is a homology.

The adjustment of channel contours to simple curves is brought about, in both classes of streams, by the more rapid erosion of projecting angles, but the work of the water is concentrated on these through the property of momentum, and the work of the ice through viscosity.

The walled causeways sometimes built by streams of ice debouching onto a plain have a different process of construction from the similar causeways occasionally built by streams of water. The walls of the glacial causeway are made by the deposition of lateral moraines that had been carried chiefly as back-load. The walls of the fluvial

causeway are made by the deposition of suspended waste through the slackening of spreading side currents.

The salient fact brought out by these comparisons is that many features of rivers and river work which arise from inertia in association with swift motion are paralleled by features of glaciers and glacier work which arise from high viscosity in association with slow motion. In each kind of stream, changes in the direction of flow are caused by irregularities of the channel, and complex series of phenomena arise from the resistance of the current to deflection. These series are strikingly parallel, but the resistance to deflection is occasioned in one case by momentum and in the other by viscosity.



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